NIF

Layering 102

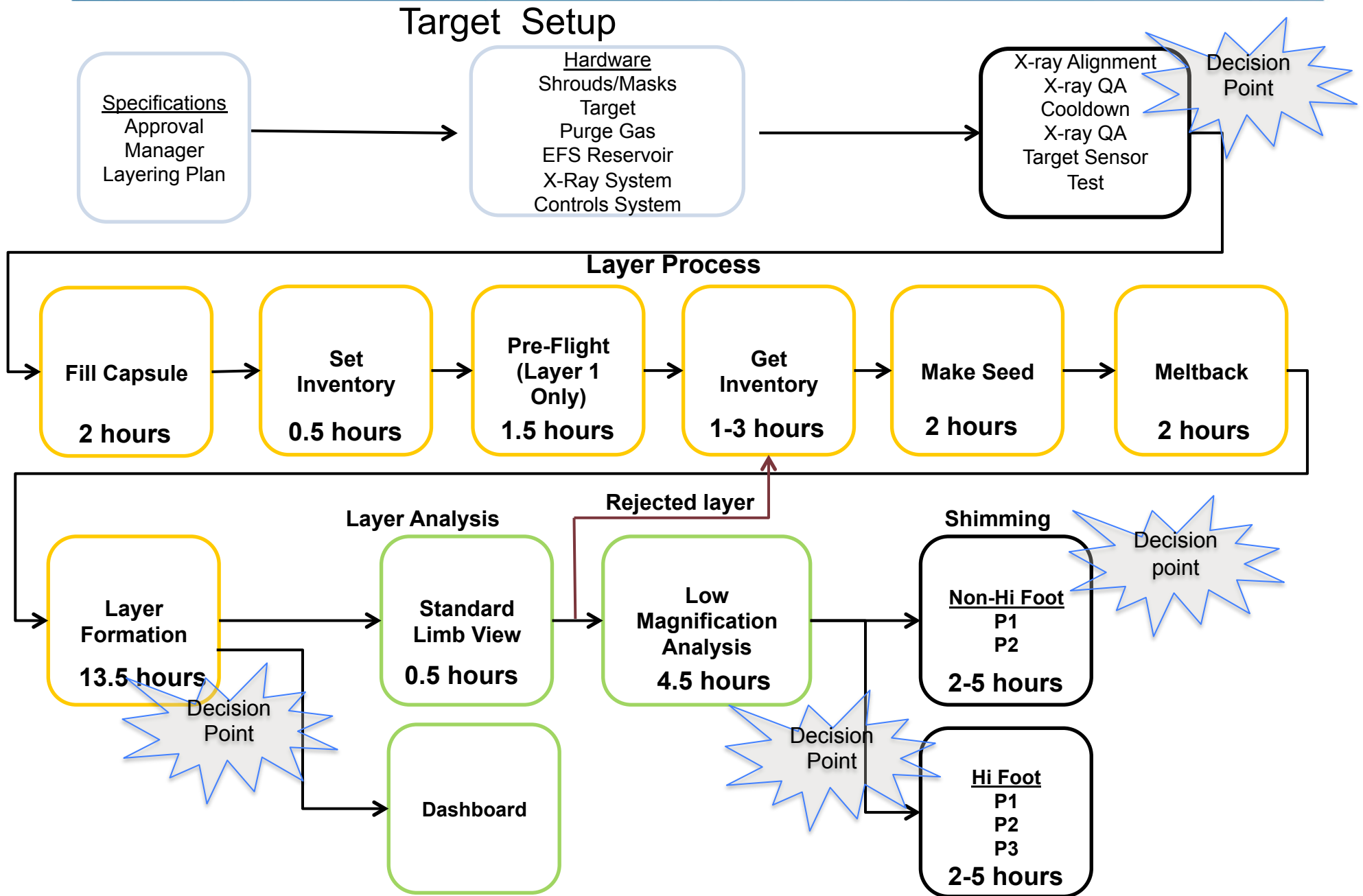# NIF is moving to a more sustainable operating mode for layering support

- Increased level of training for Cryo Operators and Field Engineers
- New training for Shot RIs on the layering process
- More reliance on Rules of Engagement to make decisions during the layering process
- Reduced off-hours support from layering SMEs

As we transition to this new mode, we want your feedback about how it's working and how we could continue to improve to assure high quality layered experiments

The layering process has four "decision points" where the operators could require input from the experimental team

NIF

Target Setup

Specifications	Hardware	X-ray Alignment
Approval	Shrouds/Masks	X-ray QA
Manager	Target	Cooldown
Layering Plan	Purge Gas	X-ray QA
	EFS Reservoir	Target Sensor
	X-Ray System	Test
	Controls System	

Decision Point

Layer Process

Fill Capsule	Set Inventory	Pre-Flight (Layer 1 Only)	Get Inventory	Make Seed	Meltback
2 hours	0.5 hours	1.5 hours	1-3 hours	2 hours	2 hours

Rejected layer

Layer Analysis

Shimming

Decision point

Layer Formation	Standard Limb View	Low Magnification Analysis	Non-Hi Foot
13.5 hours	0.5 hours	4.5 hours	P1 P2
			2-5 hours

Decision Point

Decision Point

Dashboard	Hi Foot
	P1
	P2
	P3
	2-5 hours

The changes in the process are in how the decision points are handled if they fall outside of the defined ROE

Before June FM&R	After June FM&R

• When developments with a layer are not clearly captured by the ROE, the FE and CSOs contact the SME for review and guidance
  — SMEs are available 24/7
 	
• If the SME feels a decision needs to be made outside the specifications of the ROE, the SME calls for a management review board (MRB)
	▪ When developments with a layer are not clearly captured by the ROE , the FE and CSOs contact the Shot RI for guidance
	
	▪ The Shot RI determines whether to call an MRB
	
	▪ SMEs will be available to consult or to joint the MRB M-F from 7am to 10pm
	  — SMEs may be available on weekends, but will no longer be "on call"
	
	▪ Communications to the Shot RI will be coming from the FEs and CSOs
	
	▪ The Shot RI may decide to wait to call the MRB during business hours, when the layering SME is on call

Clear and complete Rules of Engagement will be key to the success of this new paradigm

The Layering Group will continue to provide expert, high-quality support of layering activities

- With changes in personnel in the layering group and an increase in the number of layering activities anticipated, it is no longer practical to have dedicated on-call layering SME support during routine layered shot operations
- New procedures and training in are being put in place to enable NIF technicians to handle typical off-normal cases previously referred to the layering SME

Additional notes on facility support for layering after the June FM&R

- For new/unique layering activities (e.g. wetted foam, tentless targets, etc.), more layering SME support will be provided until processes are turned into routine procedures
- Early aborts for layer formation will be limited to
  — Lost seed (~ 1 hour after Form Layer begins)
  — Analysis at 9 hours after Form Layer begins. Standard limb analysis will be performed and layer evaluated against the layer quality ROE.
- Shimming is automated, depends on standard limb analysis

Overview and quick reference to reports

Expected reports from the facility that the Shot RI should be aware of

- Xray QA report – warm/cold reports on capsule sag and defects in the image view
- Layer limb analysis reports – Low shape, thickness, groove report
- Low Mag imaging report – Include possibly large defects in the central portion of the LEH view

- These slides give an overview and background material on the layering process and analysis.

Xray QA report

Xray QA report
is in Excel workbook

Tabs for 'Warm' and 'Cold'
QA for each section

C160504-AB XRay QA.xlsx (Read-Only)

Warm X-Ray QA

Step	Instructions	Data/Comments	Initial
14	Ensure that the variable capsuleSagLimit in the XRayQA.m script is equal to the value given in the layering plan.		RH
15	Run the XRayQA.m script		RH
16	The script will first compute the magnifications. Confirm that the computed green markers in each image overlaps the capsule edge, then if satisfied, click "Yes" to save the magnification values.		RH
17	XRayQA.m will calculate and display the capsule shifts and P2 measurements. Record these values below:		
	********* Side1 Capsule Shifts **********		
	Capsule sag (vertical, positive is capsule down) =	-18.93	
	Capsule horizontal offset =	12.72	
	Capsule P2 Cos =	0.13	
	Capsule P2 Sin =	-0.26	
	********* Side2 Capsule Shifts **********		
	Capsule sag (vertical, positive is capsule down) =	-19.15	
	Capsule horizontal offset =	38.79	RH
	Capsule P2 Cos =	-0.01	
	Capsule P2 Sin =	0.03	
	********* LEH Capsule Shifts **********		
	Capsule P2 Cos =	-0.24	
	Capsule P2 Sin =	-0.2	
	********* Capsule Radial Shift, Total Shift, and Side1 - Side2 Comparison **********		
	Radial shift from hohlraum axis =	40.82	
	Total shift from hohlraum center =	45.04	
	Difference between the Side1 and Side2 Capsule sags (should be less than 8 microns) =	0.22	
18	If any of the values are out of spec (cells will turn red), contact the FE/Layering SME		RH
19	If XRayQA.m does not work, run the manual version of the procedure.		N/A
20	Using the ICSS maintenance panel for the vessel cryopump valve, close the valve and confirm on the ICS GUI that the		RH
	...l, turn off the vessel cryopump. This is neded due to the fact that the vessel cryopump will not go into ...cryocooler is not running.		RH
	...n the MATLAB console, select "Track meniscus height".		RH
	...ue in "trackMeniscusImageProcessing(100);" is "100".		RH
24	Run "Track meniscus height". Wait for four images to be acquired and then confirm that the registered images have appeared on the imaging GUI. Kill track meniscus with using control c.		RH
25	Using the ICS GUI, turn the vessel cryopump back on.		RH
26	From Quicklooks, copy and paste the registered images into WarmImages Tab.		RH
27	Verify images are not clipped and X-Ray system is aligned properly.		RH
28	Inspect each image for artifacts. Record locations of all artifacts observed.		RH
	Side 1 Artifact Locations =		
	Side 2 Artifact Locations =	2:30 o'clock	

Tabs: NIF Operations Checklist | WarmQA | WarmImages | ColdQA | ColdImages | Parallax Procedure | Parallax – Warm | Parallax – Cold

Normal View | Ready | Sum=0

Xray QA report: Capsule offset report

- Tabs 'WarmQA' or 'ColdQA', show the capsule displacements for each view

Check these values, Sag measurements should agree to ~ 5 μm. Horizontal can disagree, each view see different horizontal slice

	Side1 Capsule Shifts
Capsule sag (vertical, positive is capsule down) =	-18.93
Capsule horizontal offset =	12.72
Capsule P2 Cos =	0.13
Capsule P2 Sin =	-0.26

	Side2 Capsule Shifts
Capsule sag (vertical, positive is capsule down) =	-19.15
Capsule horizontal offset =	38.79
Capsule P2 Cos =	-0.01
Capsule P2 Sin =	0.03

	LEH Capsule Shifts
Capsule P2 Cos =	-0.24
Capsule P2 Sin =	-0.2

********* Capsule Radial Shift, Total Shift, and Side1 - Side2 Comparison **********

Radial shift from hohlraum axis =	40.82
Total shift from hohlraum center =	45.04
Difference between the Side1 and Side2 Capsule sags (should be less than 8 microns) =	0.22

Xray QA: Parallax measurement is used to determine location of defects in image ('Parallax – Warm' tab)

Side1

Magnification:	1.899	Image#	

Artifact Location:			

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)				
Shifted (pix)				
Camera Shift (um)				
Capsule to Source using Magnification (um)				
X-Ray Source Motions (um)	0.00	0.00	Use value with larger source motion.	
Feature to Source (mm)	#DIV/0!	#DIV/0!		
Capsule to Feature distance (mm)	#DIV/0!	#DIV/0!	Negative values are closer to the source.	

Artifact Location:			

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)				
Shifted (pix)				
Camera Shift (um)	0	0	0	0
Capsule to Source using Magnification (um)	94.00			
X-Ray Source Motions (um)	0.00	0.00	Use value with larger source motion.	
Feature to Source (mm)	#DIV/0!	#DIV/0!		
Capsule to Feature distance (mm)	#DIV/0!	#DIV/0!	Negative values are closer to the source.	

Approximate location in images

Side2

Magnification:	1.93	Image#	2

Artifact Location:		10:00	

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)	322	412	667	226
Shifted (pix)	323	569	667	387
Camera Shift (um)	20	3140	0	3220
Capsule to Source using Magnification (um)	95.54			
X-Ray Source Motions (um)	0.00	342.92	Use value with larger source motion.	
Feature to Source (mm)	0.00	97.73		
Capsule to Feature distance (mm)	-95.54	2.19	Negative values are closer to the source.	

Artifact Location:			

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)				
Shifted (pix)				
Camera Shift (um)	0	0	0	0
Capsule to Source using Magnification (um)	95.54			
X-Ray Source Motions (um)	0.00	0.00	Use value with larger source motion.	
Feature to Source (mm)	#DIV/0!	#DIV/0!		
Capsule to Feature distance (mm)	#DIV/0!	#DIV/0!	Negative values are closer to the source.	

Features on side view are often machining burrs on starburst, even though they appear close to capsule

LEH

Magnification:	1.827	Image#	2

Artifact Location:		11:00	

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)	440	328	710	200
Shifted (pix)	381	226	630	73
Camera Shift (um)	-1180	-2040	-1600	-2540
Capsule to Source using Magnification (um)	90.44			
X-Ray Source Motions (um)	-160.85	-255.36	Use value with larger source motion.	
Feature to Source (mm)	118.76	110.14		
Capsule to Feature distance (mm)	28.3	19.70	Negative values are closer to the source.	

Artifact Location:		1:00	

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)	963	347	710	200
Shifted (pix)	894	222	630	73
Camera Shift (um)	-1380	-2500	-1600	-2540
Capsule to Source using Magnification (um)	90.44			
X-Ray Source Motions (um)	-160.85	-255.36	Use value with larger source motion.	
Feature to Source (mm)	103.35	91.75		
Capsule to Feature distance (mm)	12.91	1.31	Negative values are closer to the source.	

On shroud

Likely on capsule (closer to capsule than LEH), distance measured from center of capsule. Accuracy is not better than ~ 1-2 mm typically

Xray QA: Most 'dark spots' on the capsule are likely high-Z material

- Detected x-ray spectrum peaks about 8.5 keV
- 30% attenuation corresponds to ~ 1 µm Au, 200 µm HDC, 700 µm CH

Layer Analysis Report

- **This summary report comes via email, usually sufficient to decide to keep or reject layer**

- **Also included is a .zip file which includes more details on the layer analysis, unwrapped images.**

C151002-AA-6 LAYER COMPLETION REPORT:
Approved analysis with grooves excised

********** Defects **********
Total standard groove depth = 80.25 um
Total non-standard defect depth = 0.00 um
Largest Defect area = 1261.56 um^2 from Limb Analysis
K_highMag = 1.69 um
No low mag data reported.

********** Layer Thickness **********
SIDE1: 56.92 um
SIDE2: 56.97 um
LEH: 56.52 um
Mean thickness: 56.80 um

******** Shimmable Modes *********
Shimmable Mode 1 = 2.76 um
Shimmable Mode 2 = 0.04 um

********** Layer Shape **********

Corrected ice amplitudes in microns (from Fourier decomp/for shimming)

	Cos_1	Sin_1	Cos_2	Sin_2	Cos_3	Sin_3
SIDE1:	-0.57	2.91	0.01	-0.18	0.06	0.12
SIDE2:	0.78	2.60	0.07	-0.12	0.07	0.18
LEH:	-0.49	-0.20	-0.05	-0.08	-0.02	-0.05

Corrected amplitude (RMS) per mode in microns

	Mode1	Mode2	Mode3
Spec (um):	0.52	0.46	0.39
SIDE1:	2.10	0.13	0.10
SIDE2:	1.92	0.10	0.14
LEH:	0.37	0.07	0.04
Side-avg (l modes):	2.01	0.12	0.12
LEH (m modes):	0.37	0.07	0.04

Limb Analysis: Defects reports

Before Low Mag Image:

```
********** Defects ***********
Total standard groove depth = 80.25 um
Total non-standard defect depth = 0.00 um
Largest Defect area = 1261.56 um^2 from Limb Analysis
K_highMag = 1.69 um
No low mag data reported.
```

After Low Mag Image:

```
********** Defects ***********
Total standard groove depth = 80.25 um
Total non-standard defect depth = 0.00 um
Largest Defect area = 1261.56 um^2 from Limb Analysis
K_highMag = 1.69 um
K_lowMag = 1.69 um, based on max groove depth = 26.78 um
```

- K value is estimated from Total defect depth (Standard + Non Standard)
- Two K values reported. K_lowMag is refined estimated that depends on the maximum groove found in any view. Use the K_lowMag value if available.
- Standard defects are defects that "look like grooves". Non-standard defects are other limb analysis defects (next slide)
- Largest defect can be in either Limb Analysis or Low Mag Analysis

Defects are classified as standard and non-standard

- **Standard defects appear to be grain boundary grooves**
- **Non-standard defects include "mountains"**

Unwrapped LEH images
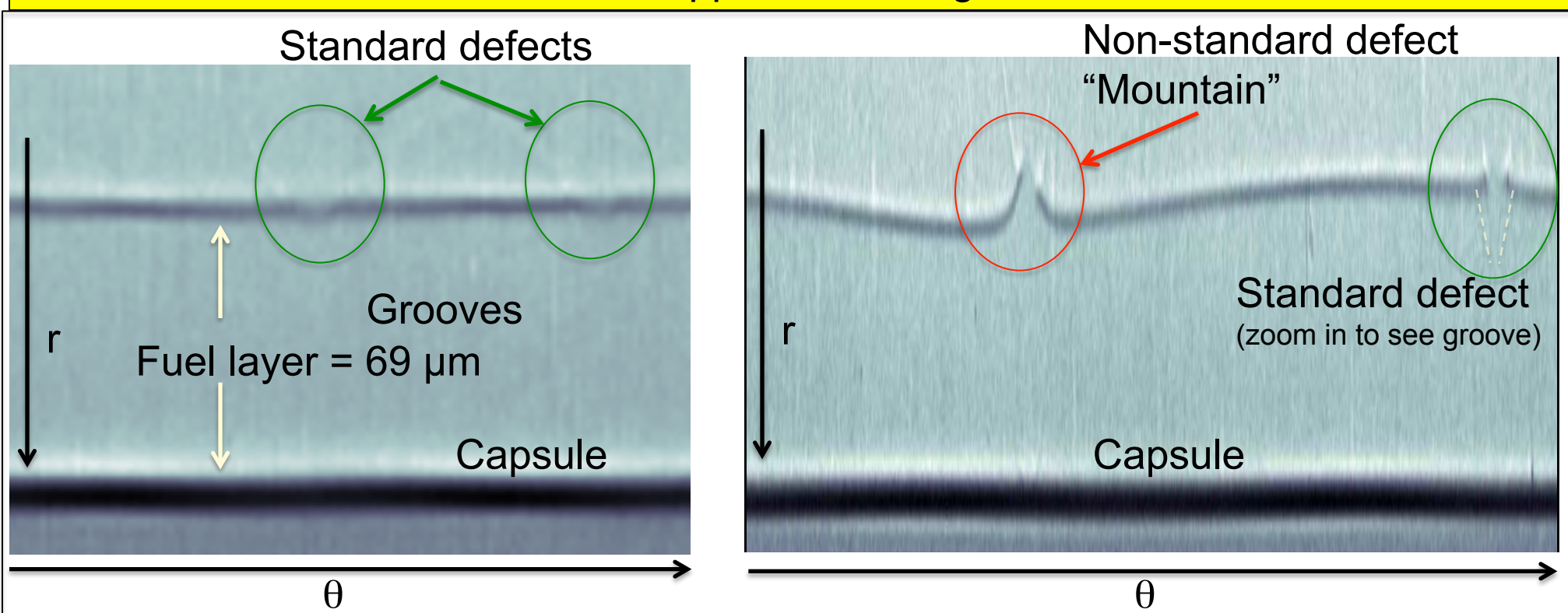
Limb Analys: Layer thickness

- **Reported for each available X-ray view (see section on Analysis)**
- **Values will be in red if outside the standard +- 1.5 μm range of desired layer thickness**
- **A "P2" can make the LEH view thickness different from the Side1 and Side 2 views.**

********** Layer Thickness **********
SIDE1: 56.92 um
SIDE2: 56.97 um
LEH: 56.52 um
Mean thickness: 56.80 um

Limb Analysis: Shimmable Modes and Layer Shape

- **Layer shape are the Fourier Cosine and Sine amplitudes, in x-ray image coordinate system (see section on Analysis).**

- **Shimmable modes can be controlled with top/bottom temperature difference (Mode 1) or shim heaters on TMP (Mode 2)**

- **Shimmable amplitude is mean of Side 1 and Side 2 views**

- **Mode 1 can be controlled in ~ 0.2 µm steps, Mode 2 in ~ 0.1 µm**

- **Corrected amplitudes are Fourier analysis after defects are removed from the DT edge profile**

```
******** Shimmable Modes *********
Shimmable Mode 1 = 2.76 um
Shimmable Mode 2 = 0.04 um
```

```
********** Layer Shape ***********
```

Corrected ice amplitudes in microns (from Fourier decomp/for shimming)

	Cos_1	Sin_1	Cos_2	Sin_2	Cos_3	Sin_3
SIDE1:	-0.57	2.91	0.01	-0.18	0.06	0.12
SIDE2:	0.78	2.60	0.07	-0.12	0.07	0.18
LEH:	-0.49	-0.20	-0.05	-0.08	-0.02	-0.05

Limb Analysis: Layer Shape

- **This report compares to the RMS mode amplitude rather than the Fourier Cosine and Sine components.**
- **First line is the standard upper limit Spec for each mode.**
- **Red values exceed spec.**
- **These are still Fourier amplitudes, not Legendre amplitudes.**

Corrected amplitude (RMS) per mode in microns

	Mode1	Mode2	Mode3
Spec (um):	0.52	0.46	0.39
SIDE1:	2.10	0.13	0.10
SIDE2:	1.92	0.10	0.14
LEH:	0.37	0.07	0.04
Side-avg (l modes):	2.01	0.12	0.12
LEH (m modes):	0.37	0.07	0.04
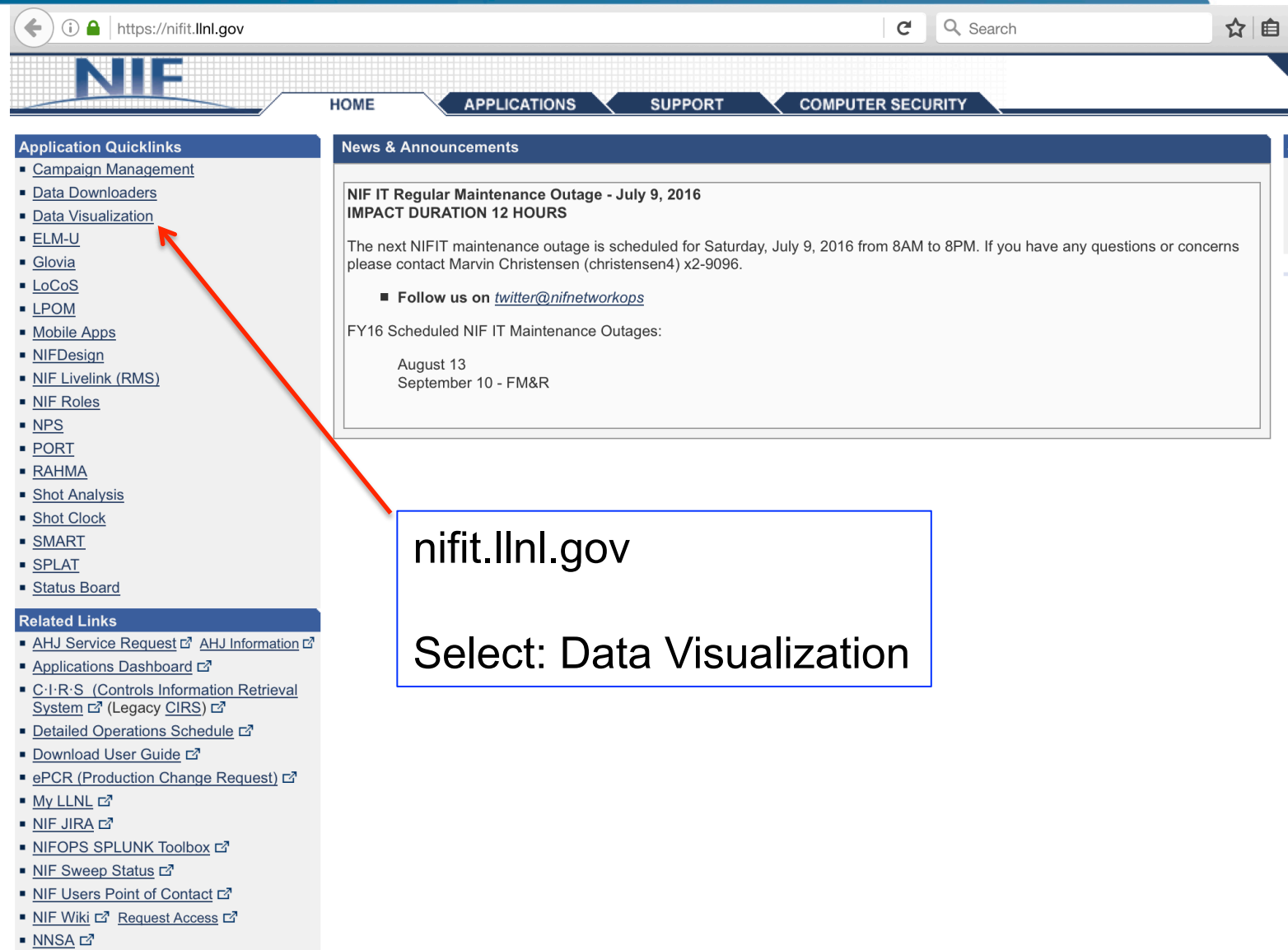
Is there enough time for another attempt? Typical timeline is ~39 hours from attempt start to shot
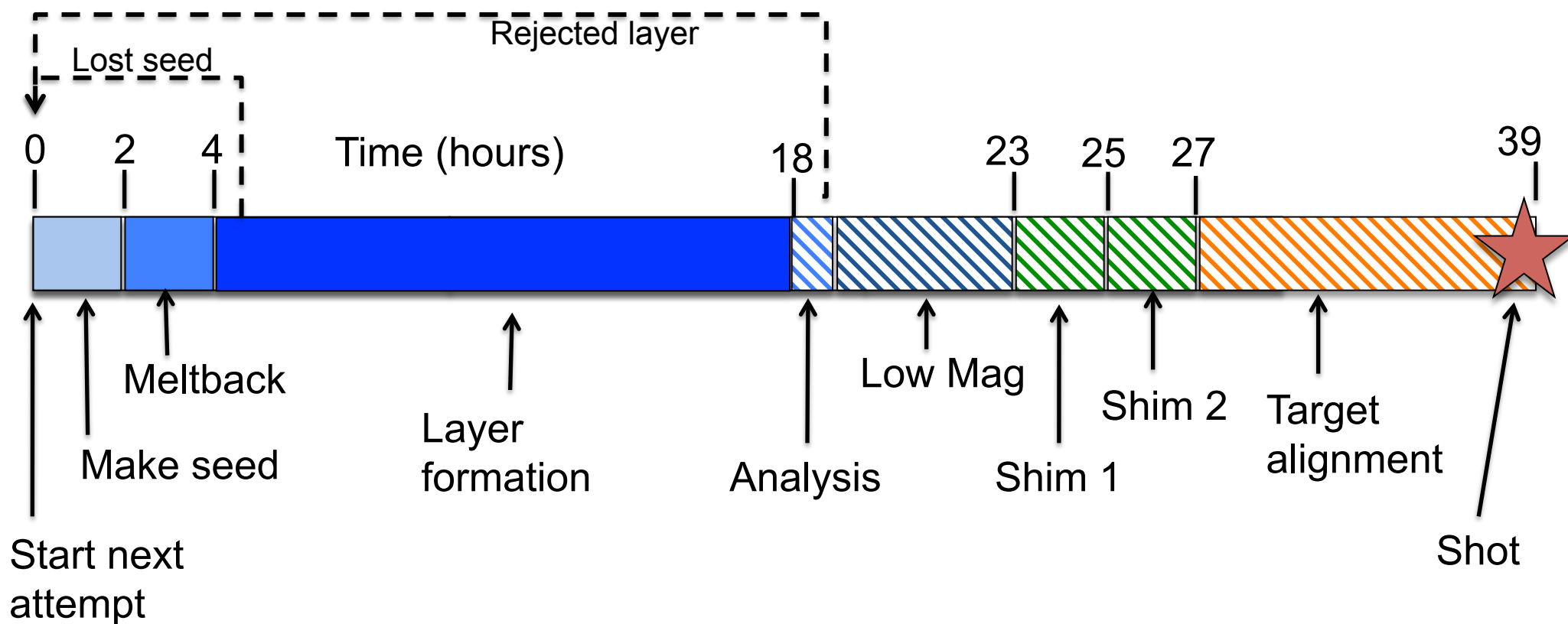
- Verify no planned ICCS restarts during (Add 2-3 hours if planned)
- Assumes target bay access available to setup for low mag and switch back to standard imaging for shimming
- Assumes seed successfully preserved in Meltback
- Length of timeline can be affected by Facility activities and staff availability – Be sure to ask Shot Director or Field Engineer for potential delays!

Getting access to CryoData via quicklooks

nifit.llnl.gov

Select: Data Visualization

Getting access to CryoData via quicklooks

Getting access to CryoData via quicklooks

Select "Cryogenics"

Getting access to CryoData via quicklooks

Select your Cryogenic Activity ExperimentID and date may give a hint

Getting access to CryoData via quicklooks

Getting access to CryoData via quicklooks

Select image view. Three Axes, Side1, Side2, LEH. _RAW images are single images, REGISTERED are an average of 4 exposures

Getting access to CryoData via quicklooks

Getting access to CryoData via quicklooks

Dashboard reports during layer formation are found under "Reports/Layering States"

Getting access to CryoData via quicklooks

First: Select "Taxon Select" CTS|TC00-015|CRYO|LAYERING-CTRL
Second: Select: recipe.dash.report.pdf

Getting access to CryoData via quicklooks

Dashboards are stored by time.
Usually want to select the most recent,
the one at the bottom.

ID	TIMESTAMP	STATE	VALUE	DETAILS
3297	05/31/2016 11:05:53.829	recipe.dash.report.pdf	dashboard report	Download
3325	05/31/2016 11:18:12.453	recipe.dash.report.pdf	dashboard report	Download
3351	05/31/2016 11:31:05.162	recipe.dash.report.pdf	dashboard report	Download
3375	05/31/2016 11:42:19.515	recipe.dash.report.pdf	dashboard report	Download
3401	05/31/2016 11:55:38.678	recipe.dash.report.pdf	dashboard report	Download
3426	05/31/2016 12:06:52.843	recipe.dash.report.pdf	dashboard report	Download
3450	05/31/2016 12:18:12.129	recipe.dash.report.pdf	dashboard report	Download
3476	05/31/2016 12:31:35.712	recipe.dash.report.pdf	dashboard report	Download
3500	05/31/2016 12:42:49.567	recipe.dash.report.pdf	dashboard report	Download
3538	05/31/2016 13:04:04.713	recipe.dash.report.pdf	dashboard report	Download
3553	05/31/2016 13:23:46.005	recipe.dash.report.pdf	dashboard report	Download
3584	05/31/2016 13:53:52.967	recipe.dash.report.pdf	dashboard report	Download
3616	05/31/2016 14:24:24.034	recipe.dash.report.pdf	dashboard report	Download
3648	05/31/2016 14:54:58.083	recipe.dash.report.pdf	dashboard report	Download
3677	05/31/2016 15:23:28.114	recipe.dash.report.pdf	dashboard report	Download
3708	05/31/2016 15:53:59.536	recipe.dash.report.pdf	dashboard report	Download
3740	05/31/2016 16:24:32.381	recipe.dash.report.pdf	dashboard report	Download
3770	05/31/2016 16:53:13.059	recipe.dash.report.pdf	dashboard report	Download
3801	05/31/2016 17:23:55.980	recipe.dash.report.pdf	dashboard report	Download
3833	05/31/2016 17:54:38.932	recipe.dash.report.pdf	dashboard report	Download
3863	05/31/2016 18:23:15.458	recipe.dash.report.pdf	dashboard report	Download
3894	05/31/2016 18:53:55.278	recipe.dash.report.pdf	dashboard report	Download
3926	05/31/2016 19:24:36.556	recipe.dash.report.pdf	dashboard report	Download
3956	05/31/2016 19:53:20.380	recipe.dash.report.pdf	dashboard report	Download
3977	05/31/2016 20:12:05.809	recipe.dash.report.pdf	dashboard report	Download
3983	05/31/2016 20:16:33.113	recipe.dash.report.pdf	dashboard report	Download
3990	05/31/2016 20:21:06.743	recipe.dash.report.pdf	dashboard report	Download
4027	05/31/2016 20:41:50.403	recipe.dash.report.pdf	dashboard report	Download
4063	05/31/2016 21:12:32.138	recipe.dash.report.pdf	dashboard report	Download
4095	05/31/2016 21:42:08.688	recipe.dash.report.pdf	dashboard report	Download
4127	05/31/2016 22:12:53.171	recipe.dash.report.pdf	dashboard report	Download
4157	05/31/2016 22:41:34.897	recipe.dash.report.pdf	dashboard report	Download

Getting access to CryoData via quicklooks

Shortcut to the most recent Dashboard report on the Cryo Quicklooks page

Overview and details of layering

Every layered target has a different experience, but they all suffer the same fate.

B381

Build
Proof: leaks, sensors, sag (warm)

B298/ITPS

Proof: leaks, sensors, sag (cryo), fill, visual, low modes
Tritium exposure

Prep: Install target, warm QA, pump/purge, cool down, pump/purge capsule, fill hohlraum, reservoir install

B581   **Layering**

Shot

Average ~ 60 hrs to accepted layer, 3.7 attempts
Shimming
Characterization

B331

Fill bottle, analyze
^{3}He purge
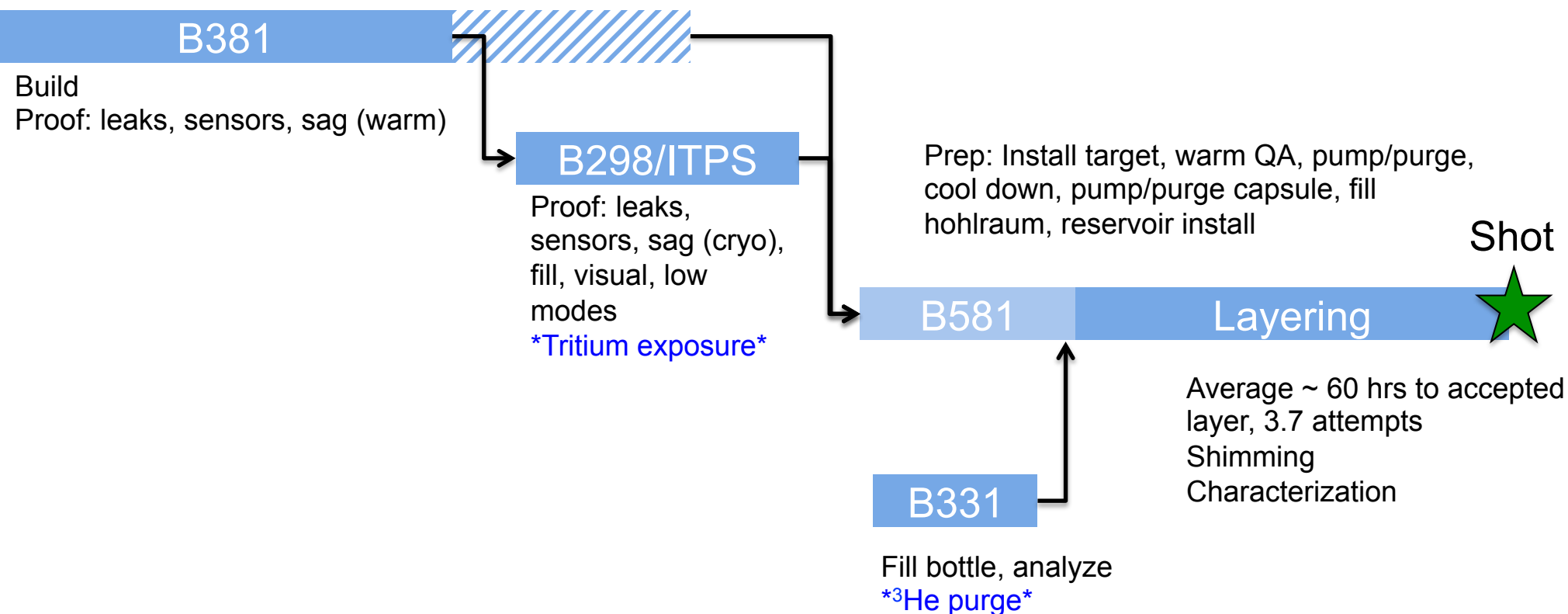
A layered target may sit, untouched, for < 12 hours to many days.

NIF cryogenic targets are mounted on the end of a precision positioning boom with integral cryo-cooler

Cryo-TARPOS

≈15 m

- **Ignition Target Inserter Cryostat (I-TIC)**
  - **Cryogenic system**
  - **Mechanical cryocooler**

- X-ray imaging for fuel ice layer characterization
- Target handling glove box

≈2.0 m

Target

Cryo-cooler
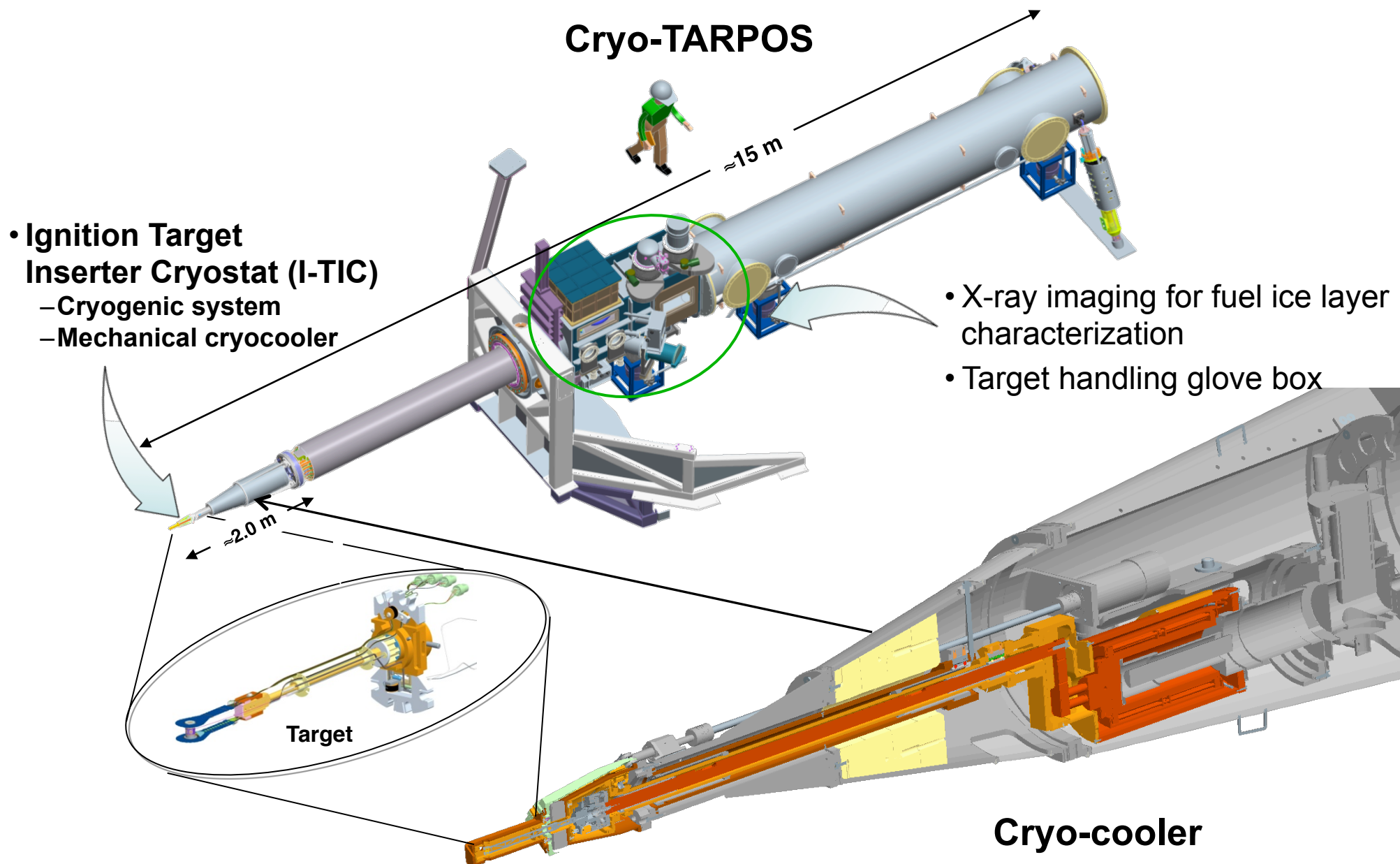
THD – THD/DT ignition target

1. Shot temperature: ~18 - 19 K
2. Target will be filled at NIF using the external fuel source (EFS) filled in tritium facility
3. Target has 'on-board' reservoir used to fine-tune amount of fuel in capsule
4. Hohlraum will be filled with He, tamps wall motion AND conductively cools capsule

On-board reservoir (not visible)

Base (attaches to cryostat)

Si Arm under dimpled shield

Target

Cold trap (for Hohlraum and capsule gases)
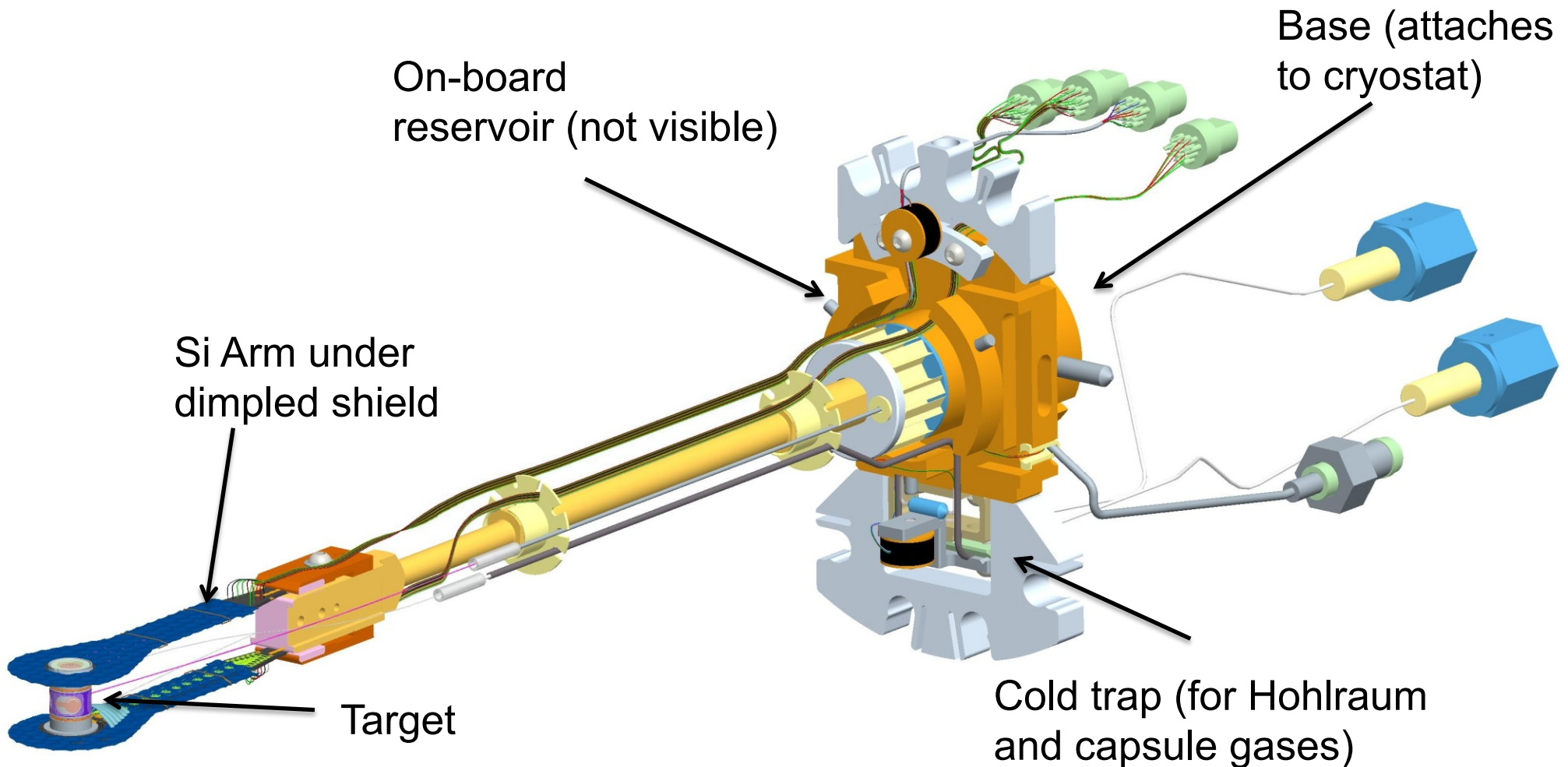
# THD target has 4 thermometers and 4 heaters

- **Sensors and heaters on TMP (Thermal-Mechanical Package) and on the silicon arms**

- **TMP heaters (HT1 and HT3) are used for P2 shimming**

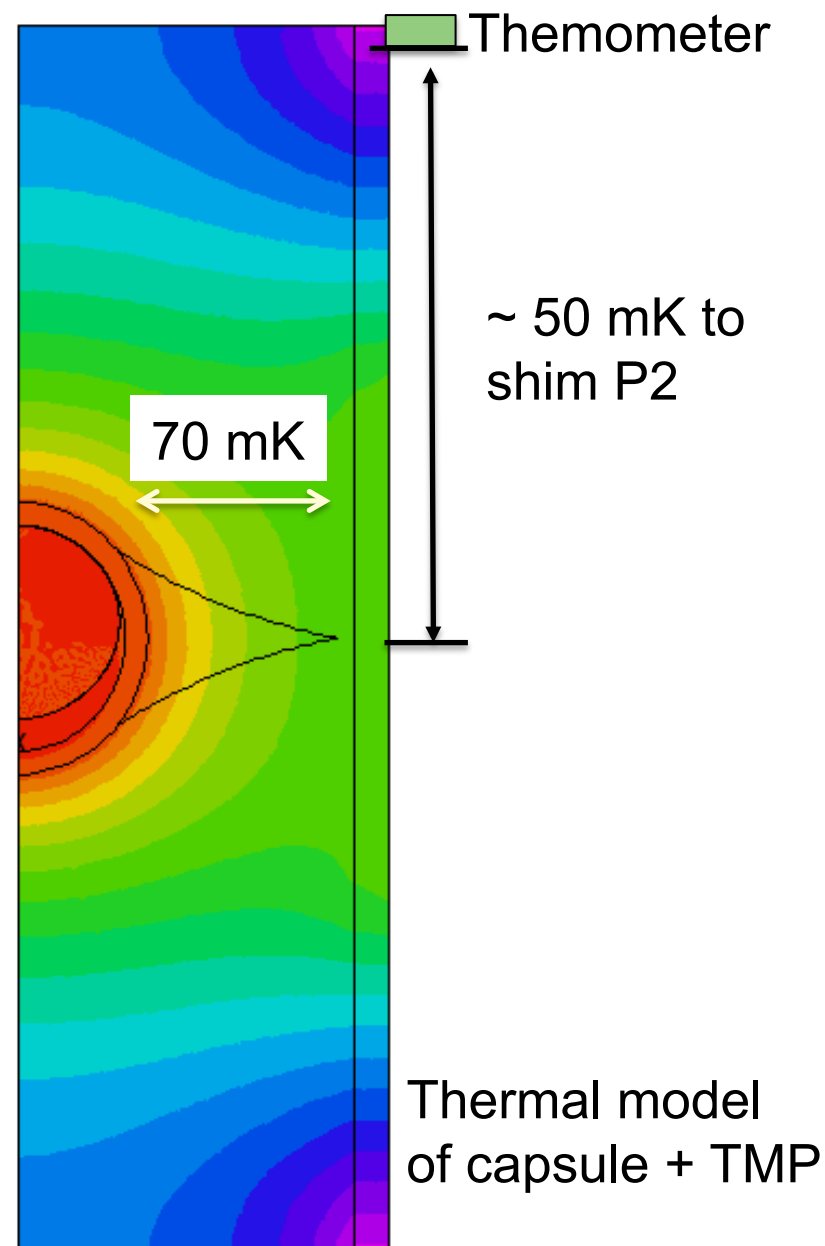- **Arm heaters (HT5 and HT7) are used to set target average temperature and P1 shimming**

TMP and arms
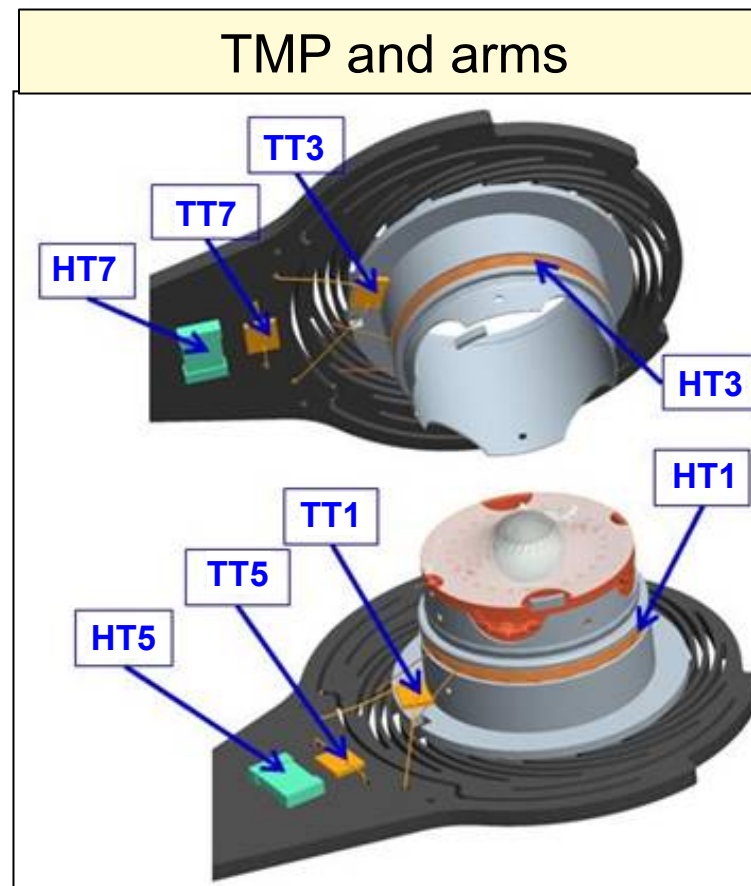
HT = heater, TT = thermometer

DT is a heat source that generates temperature gradients in hohlraum fill gas

- Shim heaters
- Silicon Arms
- TMP thermometers
- Silicon Arms

- Themometer
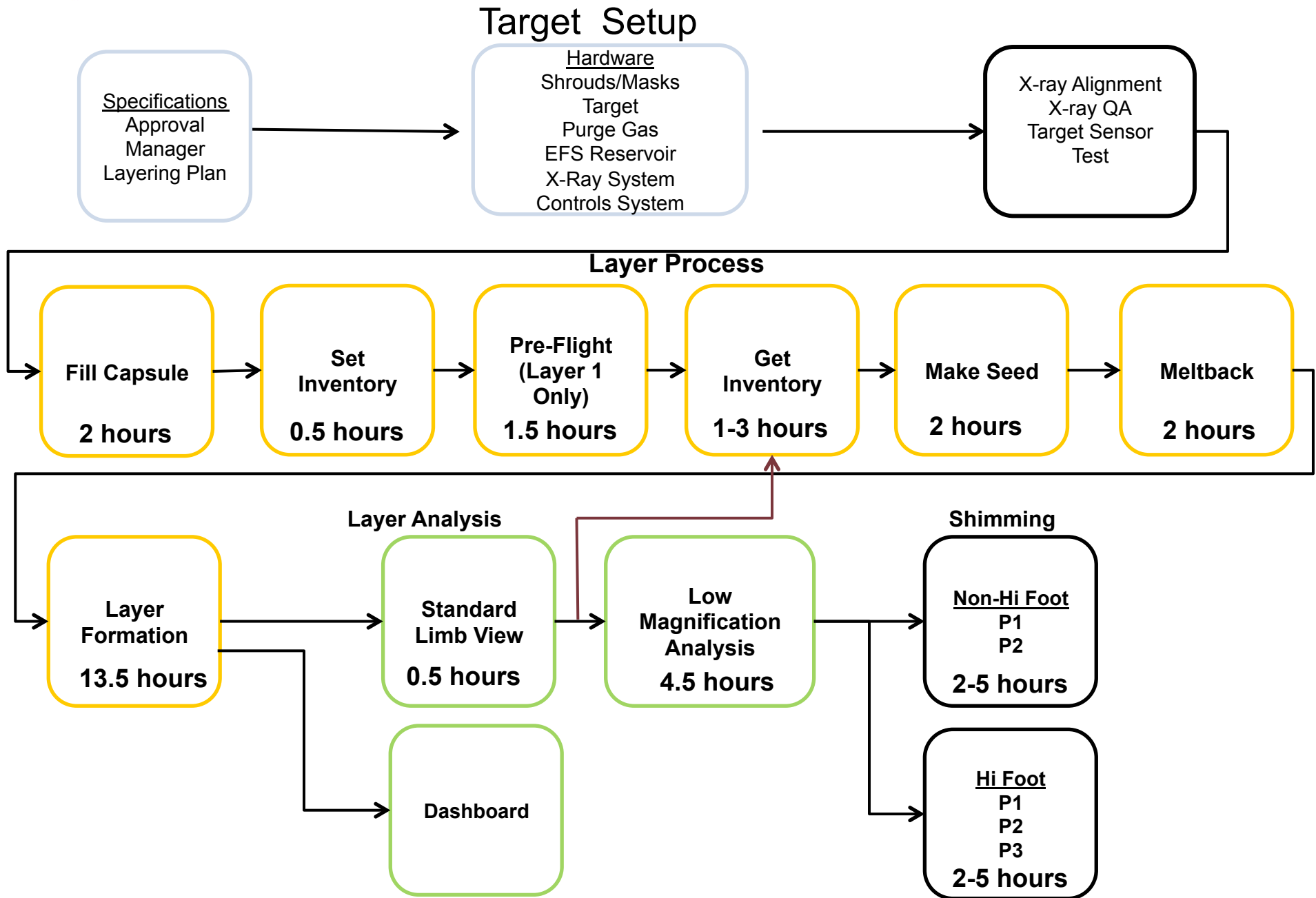- ~ 50 mK to shim P2
- 70 mK
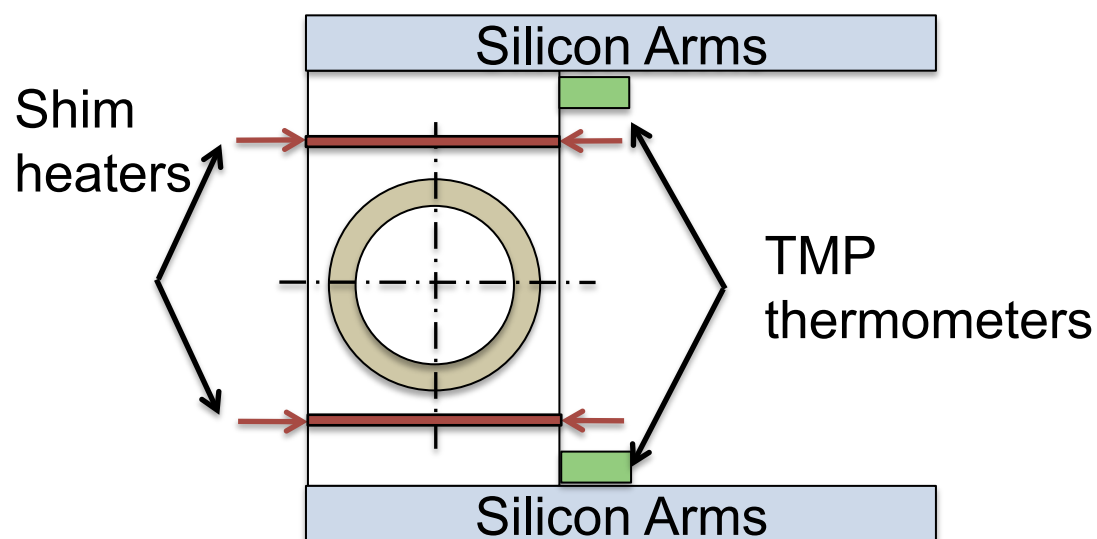
- TMP thermometers do not measure the DT temperature directly
- Offset is different for DT and D_2 because DT is a heat source, D_2 is not
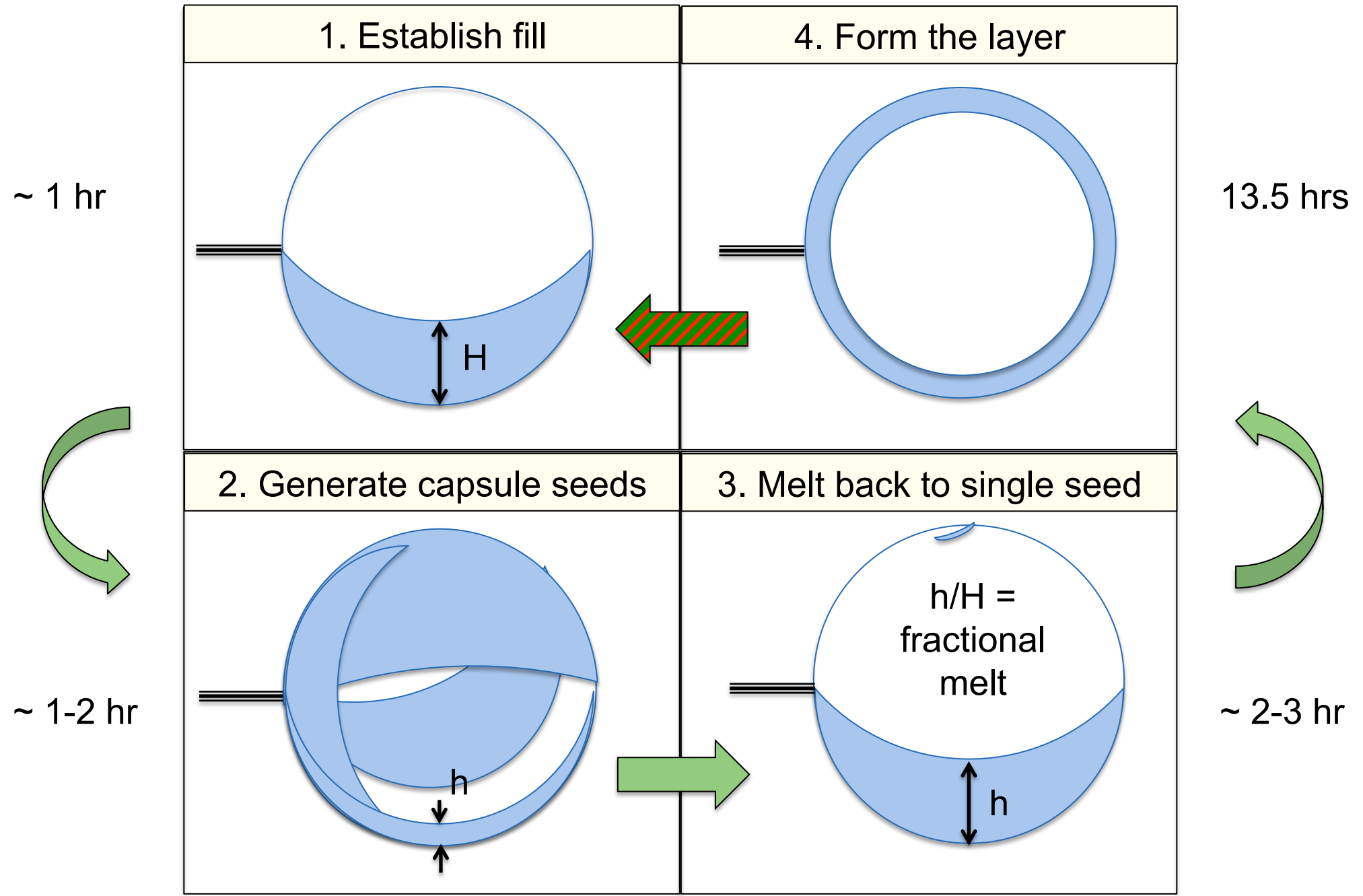- Hohlraum size changes temperature offset

Thermal model of capsule + TMP

Layering from start to shot

Target Setup

Specifications
Approval
Manager
Layering Plan

→

Hardware
Shrouds/Masks
Target
Purge Gas
EFS Reservoir
X-Ray System
Controls System

→

X-ray Alignment
X-ray QA
Target Sensor
Test

Layer Process

| Fill Capsule

2 hours | → | Set Inventory

0.5 hours | → | Pre-Flight (Layer 1 Only)

1.5 hours | → | Get Inventory

1-3 hours | → | Make Seed

2 hours | → | Meltback

2 hours |

Layer Formation

13.5 hours

Layer Analysis

Standard Limb View

0.5 hours

Low Magnification Analysis

4.5 hours

Dashboard

Shimming

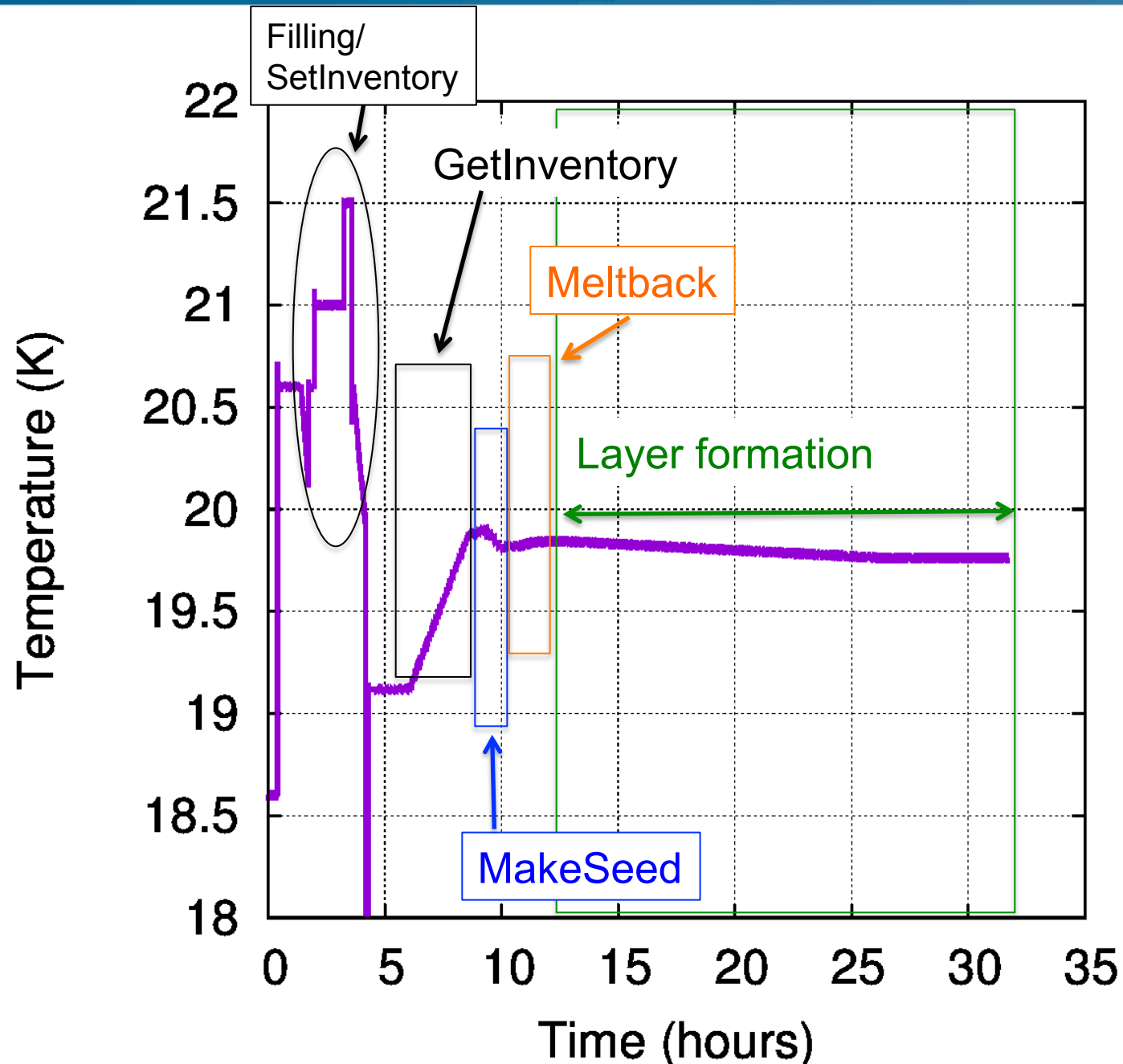**Non-Hi Foot**
P1
P2

2-5 hours

Hi Foot
P1
P2
P3

2-5 hours

The layering process centers around an attempt to isolate a single seed of the proper phase

Layering process temperature vs time
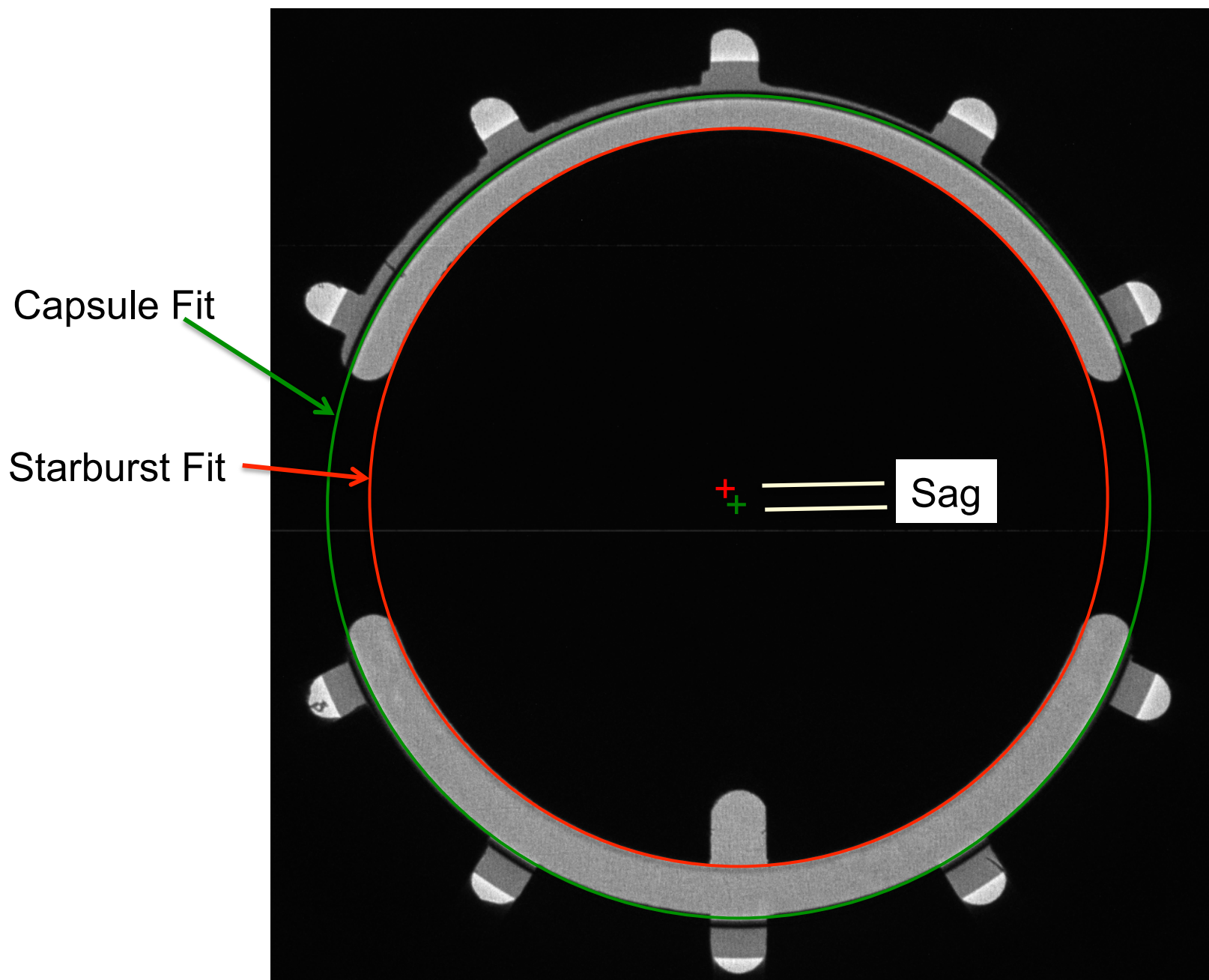
X-ray QA checks target after install in cryotarpos

- Sag in side views is measured relative to inner starburst cutout
  - Capsule center is found, starburst center found. Sag is the difference
  - Errors in machining starburst or positioning of hohlraum can throw off sag measurement. Not much better than +- 4 microns.
  - Sag can change as target is cooled. Usually best to wait until target is cold to act on sag
- Particles on capsule measured using parallax measurement
  - X-ray source moved, displacement of features with respect to the capsule gives relative location
  - Only accurate to +- 1 or 2 mm in Z location, so we can tell if particle is *likely* on capsule, LEH, or shroud windows.
  - Opacity is rough measure of thickness
    - 70% transmission corresponds to ~ 1 μm Au
    - 70% transmission corresponds to ~ 700 μm CH
    - 70% transmission corresponds to ~ 200 μm HDC
    - Dark spots are very likely Au/DU.

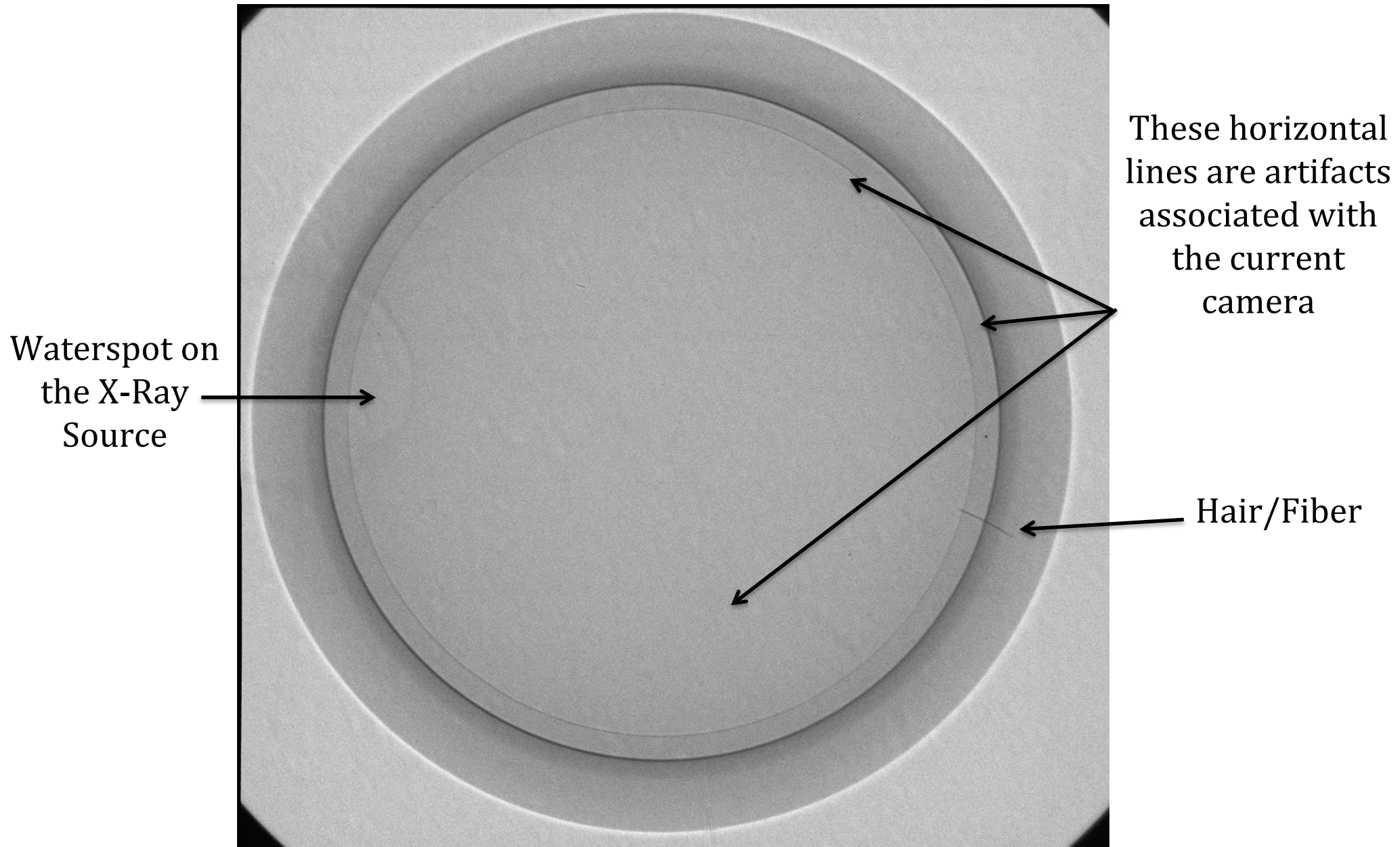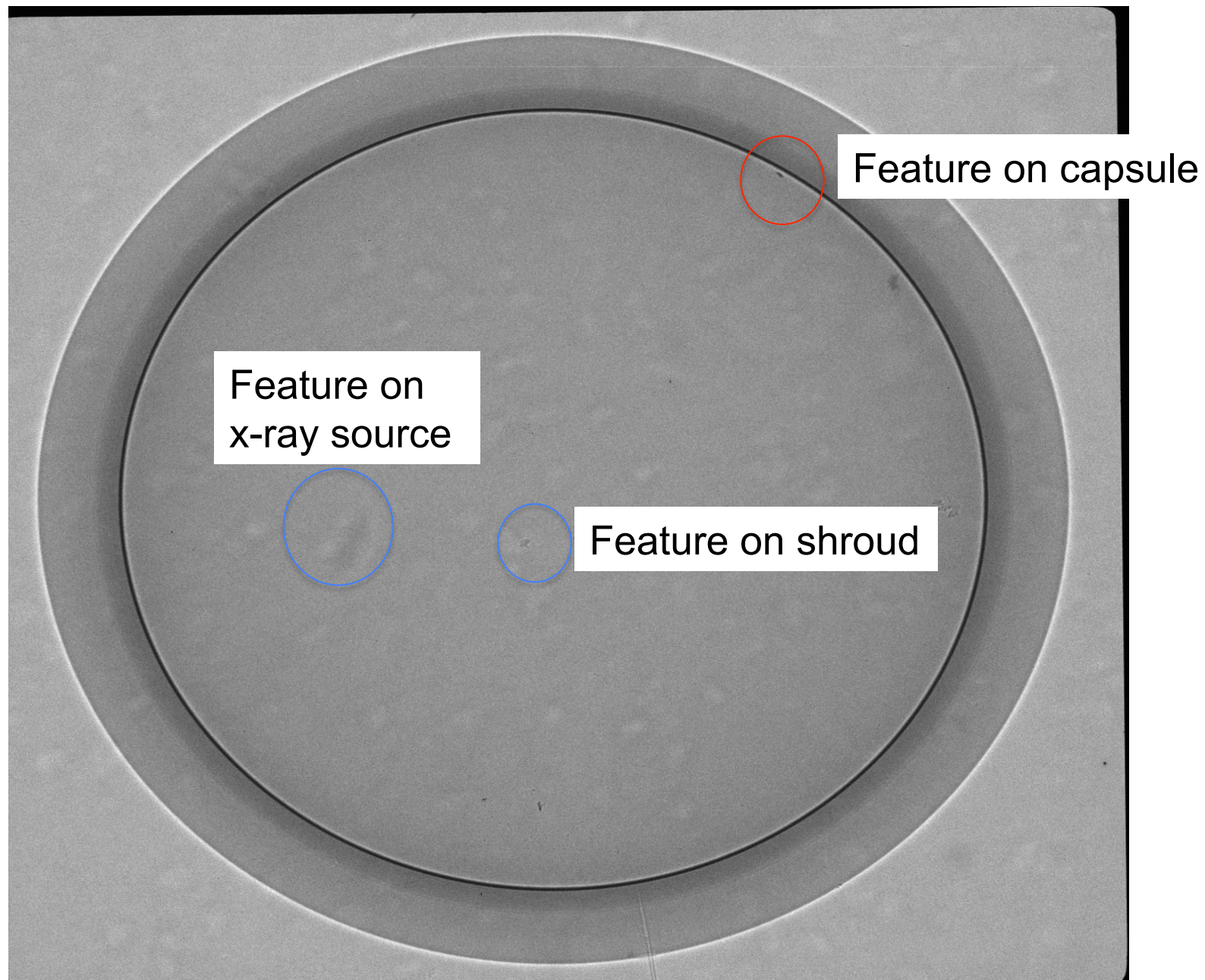# X-ray QA image from side view shows circle fits and calculated centers

Capsule Fit

Starburst Fit

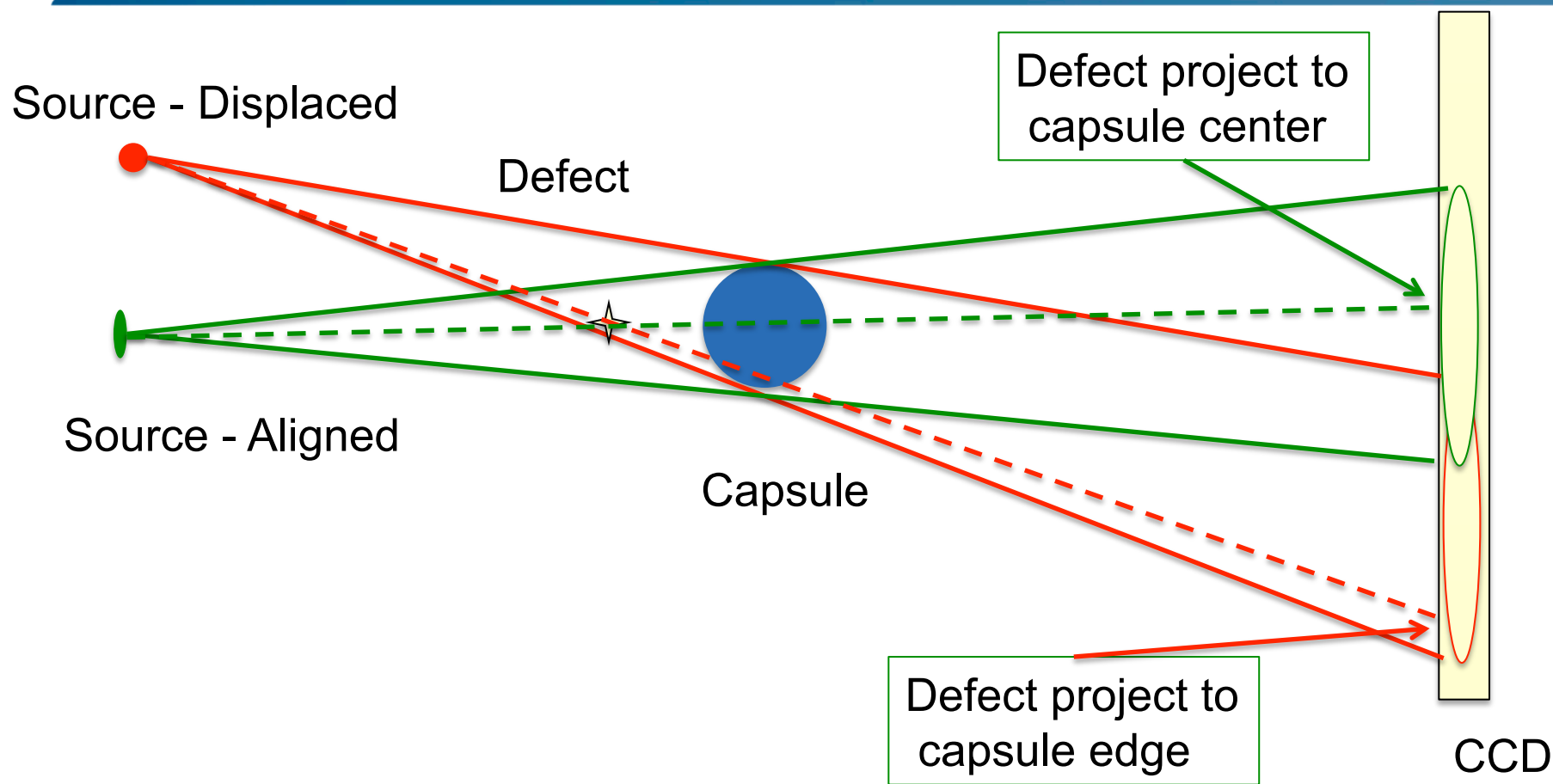Sag

Example X-Ray QA image

These horizontal lines are artifacts associated with the current camera

Waterspot on the X-Ray Source

Hair/Fiber

X-Ray QA

Feature position is determined by moving x-ray source and taking advantage of parallax

Source - Displaced

Defect

Defect project to capsule center

Source - Aligned

Capsule

Defect project to capsule edge

CCD

- **Apparent shift relative to capsule gives distance from capsule**
- **Features on capsule do not move relative to capsule**
- **Feature on CCD don't move when source is moved**
- **Maximize displacement of source to achieve best measure of feature location**

Example output from parallax measurement

Side1

| Magnification: | 1.899 | Image# | | |

Artifact Location:

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)				
Shifted (pix)				
Camera Shift (um)	0	0	0	0
Capsule to Source using Magnification (um)	94.00			
X-Ray Source Motions (um)	0.00	0.00	Use value with larger source motion.	
Feature to Source (mm)	#DIV/0!	#DIV/0!		
Capsule to Feature distance (mm)	#DIV/0!	#DIV/0!	Negative values are closer to the source.	

Artifact Location:

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)				
Shifted (pix)				
Camera Shift (um)	0	0	0	0
Capsule to Source using Magnification (um)	94.00			
X-Ray Source Motions (um)	0.00	0.00	Use value with larger source motion.	
Feature to Source (mm)	#DIV/0!	#DIV/0!		
Capsule to Feature distance (mm)	#DIV/0!	#DIV/0!	Negative values are closer to the source.	

Side2

| Magnification: | 1.93 | Image# | 2 | |

Artifact Location: 10:00

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)	322	412	667	226
Shifted (pix)	323	569	667	387
Camera Shift (um)	20	3140	0	3220
Capsule to Source using Magnification (um)	95.54			
X-Ray Source Motions (um)	0.00	342.??	Use value with larger source motion.	
Feature to Source (mm)	0.00	97.73		
Capsule to Feature distance (mm)	-95.54	2.19	Negative values are closer to the source.	

Artifact Location:

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)				
Shifted (pix)				
Camera Shift (um)	0	0	0	0
Capsule to Source using Magnification (um)	95.54			
X-Ray Source Motions (um)	0.00	0.00	Use value with larger source motion.	
Feature to Source (mm)	#DIV/0!	#DIV/0!		
Capsule to Feature distance (mm)	#DIV/0!	#DIV/0!	Negative values are closer to the source.	

LEH

| Magnification: | 1.827 | Image# | 2 | |

Artifact Location: 11:00

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)	440	328	710	200
Shifted (pix)	381	226	630	73
Camera Shift (um)	-1180	-2040	-1600	-2540
Capsule to Source using Magnification (um)	90.44			
X-Ray Source Motions (um)	-160.85	-255.36	Use value with larger source motion.	
Feature to Source (mm)	118.76	110.14		
Capsule to Feature distance (mm)	28.33	19.70	Negative values are closer to the source.	

Artifact Location: 1:00

	Artifact		Capsule	
	X	Y	X	Y
Aligned (pix)	963	347	710	200
Shifted (pix)	894	222	630	73
Camera Shift (um)	-1380	-2500	-1600	-2540
Capsule to Source using Magnification (um)	90.44			
X-Ray Source Motions (um)	-160.85	-255.36	Use value with larger source motion.	
Feature to Source (mm)	103.35	91.75		
Capsule to Feature distance (mm)	12.91	1.31	Negative values are closer to the source.	

Features on side view are often machining burrs on starburst, even though they appear close to capsule

**Potentially on capsule Distance measured from center of capsule**

45

Layering from start to shot

Target Setup

Specifications
Approval
Manager
Layering Plan

→

Hardware
Shrouds/Masks
Target
Purge Gas
EFS Reservoir
X-Ray System
Controls System

→

X-ray Alignment
X-ray QA
Target Sensor
Test

Layer Process

| Fill Capsule 2 hours | Set Inventory 0.5 hours | Pre-Flight (Layer 1 Only) 1.5 hours | Get Inventory 1-3 hours | Make Seed 2 hours | Meltback 2 hours |

Rejected layer

Layer Analysis

Layer Formation 13.5 hours

Standard Limb View 0.5 hours

Low Magnification Analysis 4.5 hours

Shimming

Non-Hi Foot
P1
P2
2-5 hours

Dashboard

Hi Foot
P1
P2
P3
2-5 hours

Filling is the process of getting fuel from External Fuel Source (EFS) to target reservoir + capsule

- Target reservoir ~ 23-30 K
- Typical pressure in reservoir + capsule is 250 torr after filling
- Capsule filled by adjusting reservoir temperature to increase pressure in capsule, condense liquid
- Manual process to start condensing liquid in capsule

EFS

Room Temperature

Valve

Target Reservoir

1 cc
23-30 K

0.004 cc
19-22 K

Cold Target
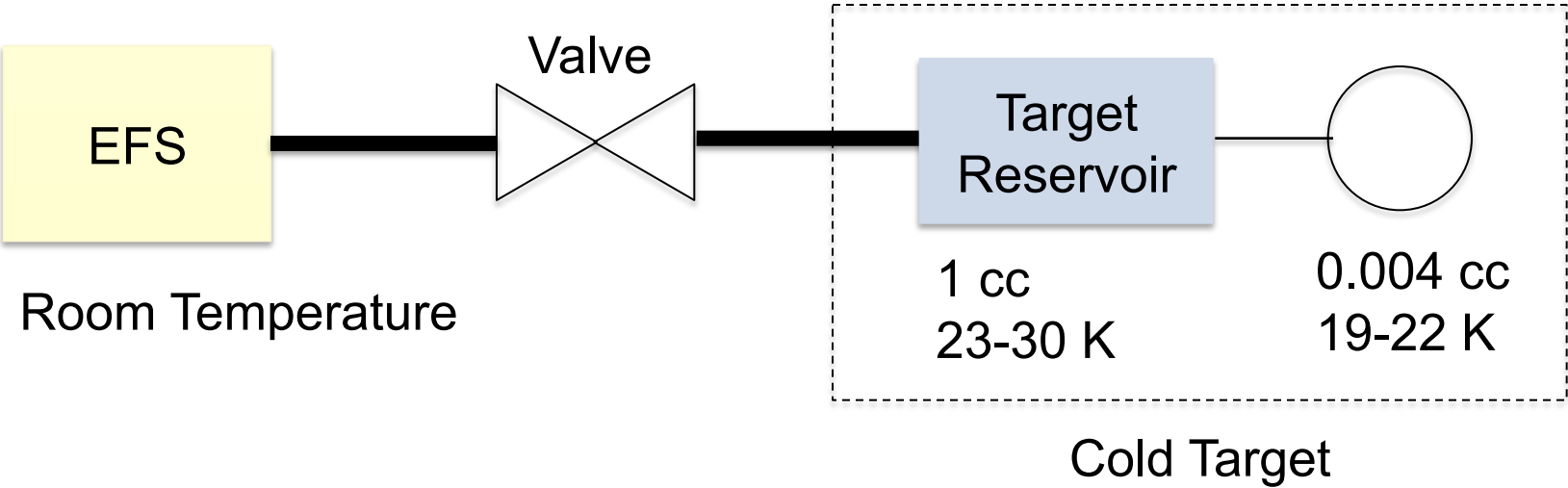
Capsule filling rate control by relative temperature of reservoir and capsule

- **Reservoir pressure follows ideal gas law: P ~ T**
- **Pressure over liquid follows saturated vapor pressure curve for liquid DT**

Target Reservoir

1 cc
23-30 K

0.004 cc
19-22 K

Cold Target

DT pressures in target

Capsule

Reservoir cannot condense liquid

Reservoir

Reservoir can condense liquid

Ideal Gas
Liq. vapor press.

Pressure (torr)
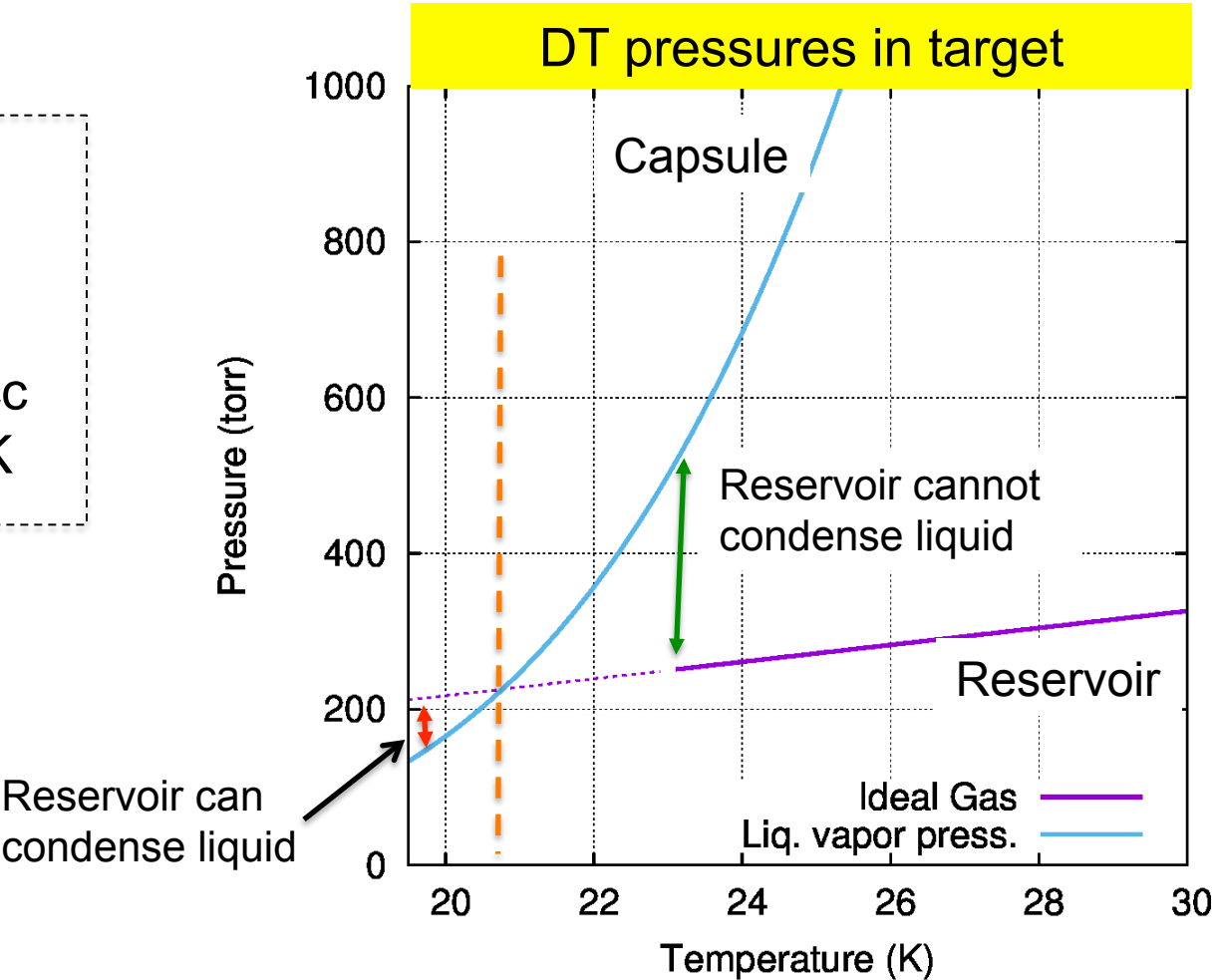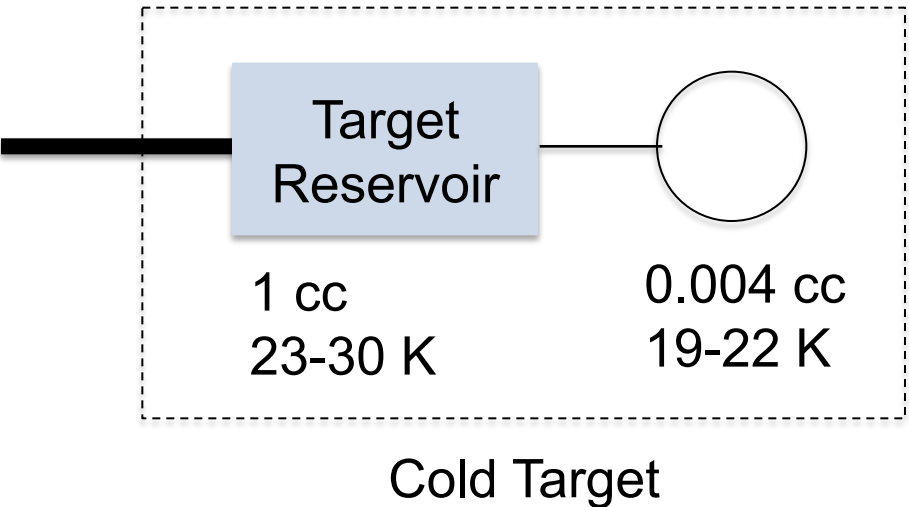
Temperature (K)

Automated routine Set Inventory tracks liquid level in capsule

- **Purpose: Set liquid level that will produce desired solid layer thickness**
  - — **Lookup table translates solid thickness to liquid level**
  - — **Capsule temperature lowered to draw in liquid from target reservoir**
  - — **Capsule temperature dropped rapidly (~ 8 K in ~ 10 seconds) when desired liquid height achieved to stop filling**

Set Inventory timeline

Capsule temperature lowered to fill

Fuel frozen, inventory set
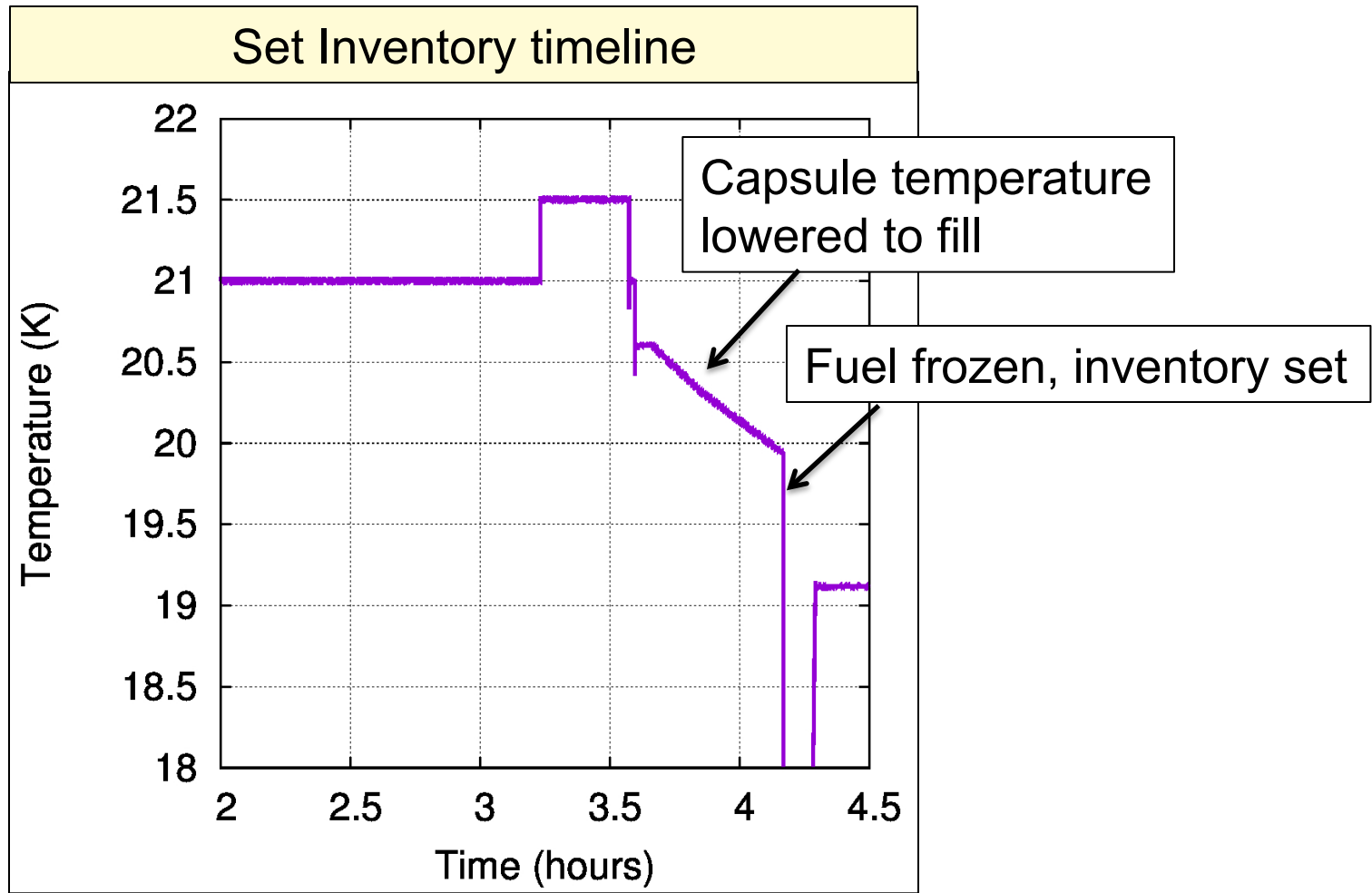
Preflight

- **Purpose: Use the flash-frozen layer from Set Inventory, allow to beta-layer and check for gross P1.**
  - **Holds temperature for 90 minutes to allow solid to redistribute to nearly final shape**
  - **Good for determining large P1 (> 5 μm) to reduce amount of shimming needed in final layer**
- **Layer is usually too rough to make an adjustment for P2**
  - **P2 value with no shim current applied is -2.6 μm for a standard target (some target are less). Measurement of rough layer isn't better than this**

Get Inventory

- **Purpose: Steps temperature rapidly to get approximate melting temperature for this target.**

Get Inventory timeline
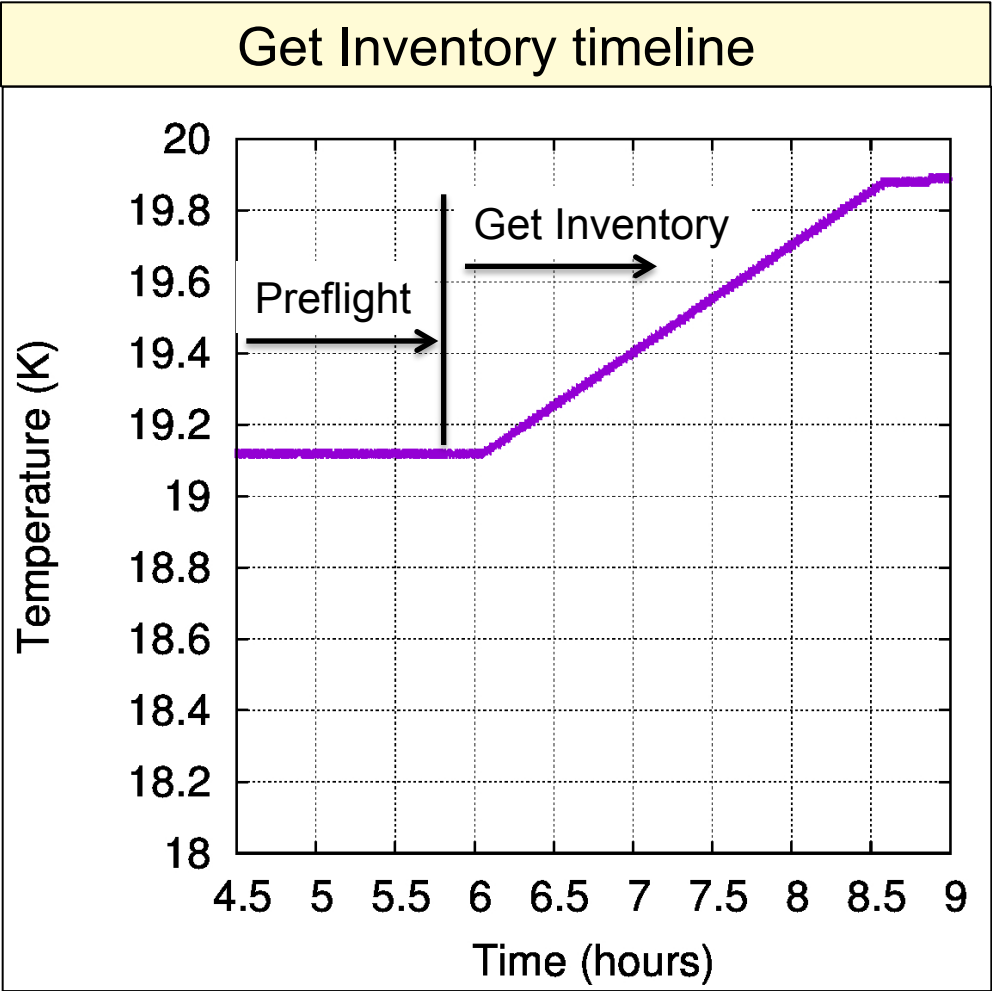
Make Seed

- **Purpose: First determine liquid height when fully melted. Then reduce capsule temperature until solidification starts**
  - **Steps up temperature to verify completely melted. Averages liquid height measurement over several image cycles**
  - **Then steps temperature down looking for change in liquid height that indicates solid forming**
  - **Waits 20 minutes for solid to stabilize before proceeding**
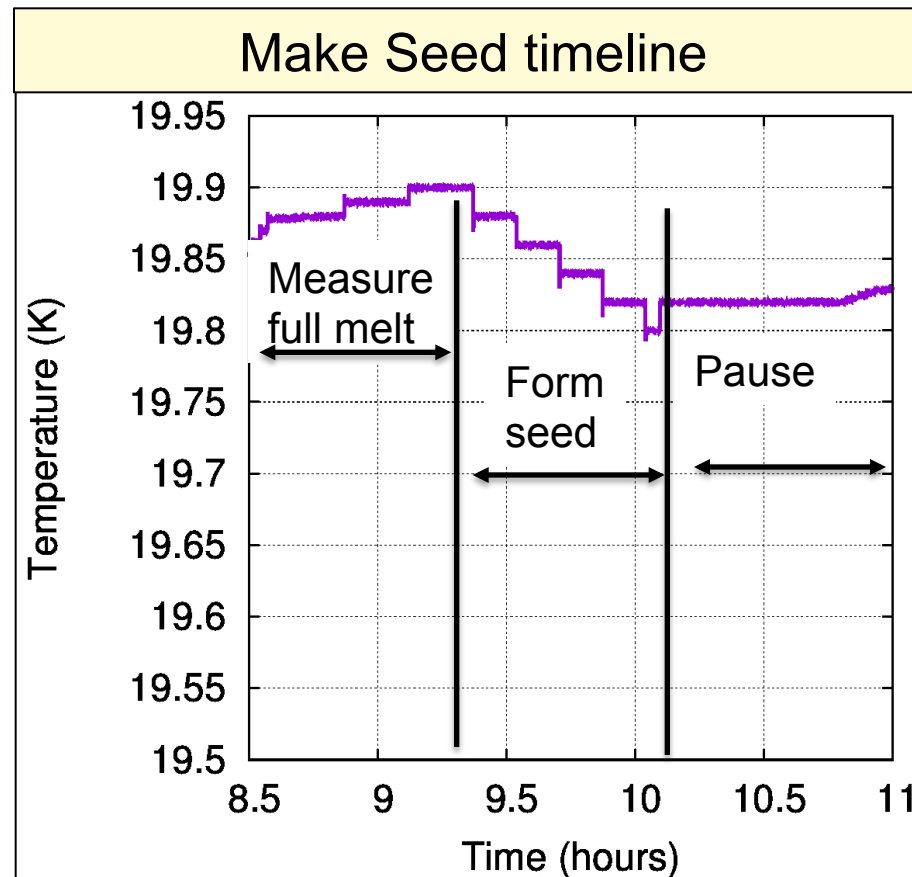
Meltback

- **Purpose: Isolate a small seed crystal in the capsule**
  - **Steps temperature slowly, compares liquid height to fully melted value determined in Make Seed**
  - **When liquid height is within 'mtol' (meniscus tolerance), stops increasing temperature and proceeds to Layer Formation**

Meltback timeline
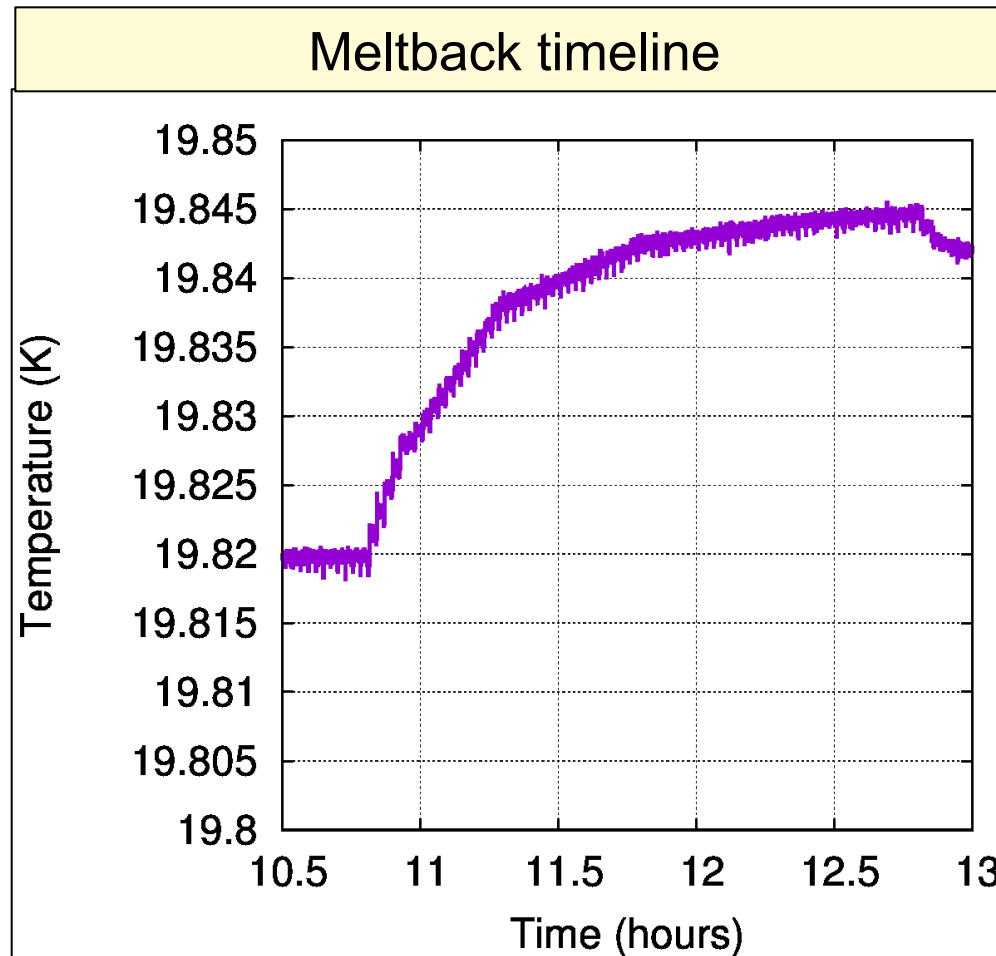
Seed crystal is made by tracking melting in 3 x-ray views

Side view x-ray image

Visible solid

g

Liquid meniscus

Liquid height

Fractional melt height

Full Melt

Slow approach to desired melt fraction ~ 0.999

Melt Fraction

Time (min)
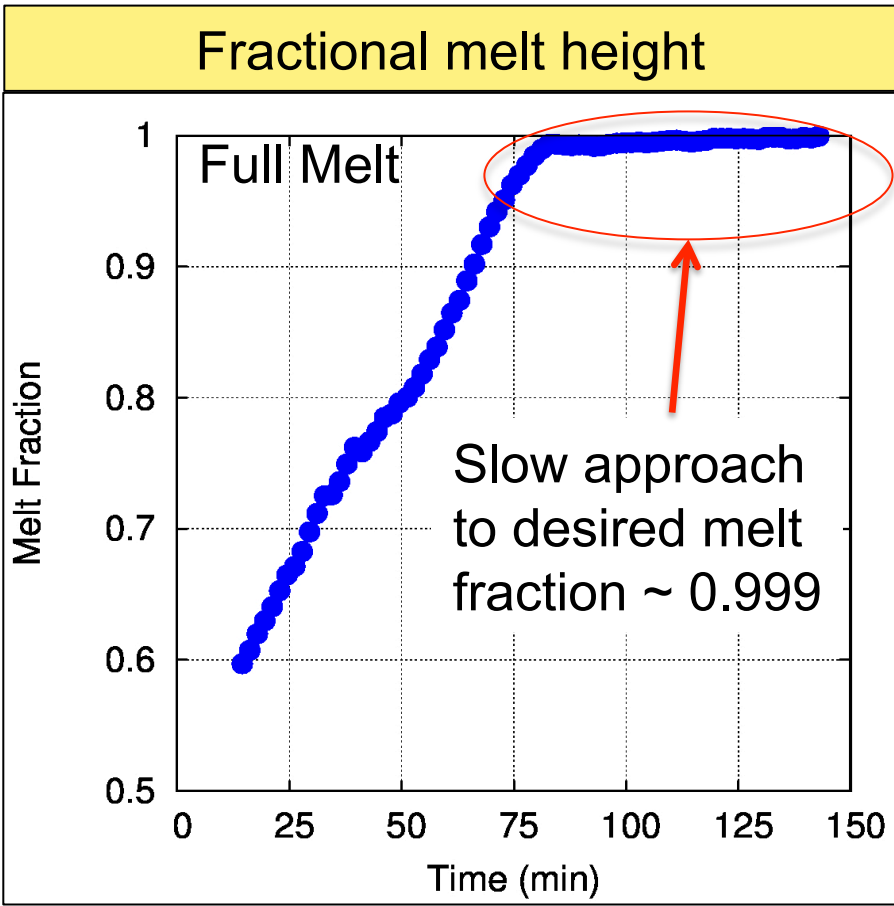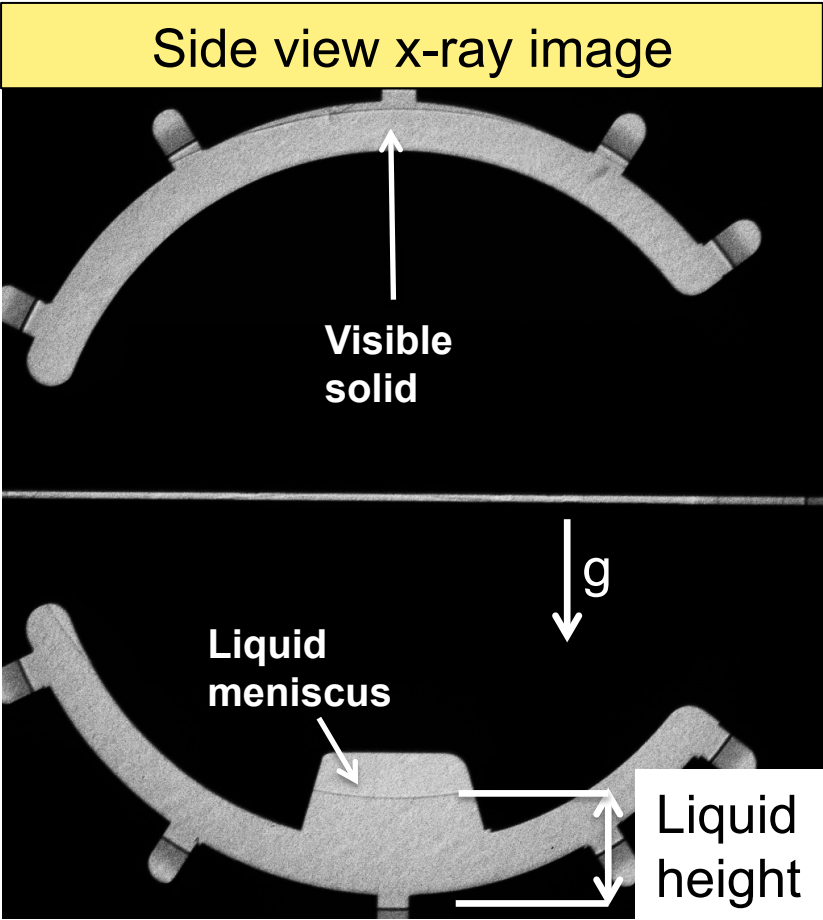
Layer Formation

- **Purpose: Slowly cool capsule to form solid layer from seed crystal**
    - **Standard cooling rate is 0.080 K over 13.5 hours for DT, 0.350 K over 17 hours for HDT.**
    - **Lost seed if no change in liquid height within 45 minutes of start**
        - **Restart at MakeSeed if seed is lost**
    - **Layer is typical stable for first good look at 9 hours into solidification**

Layer Formation timeline
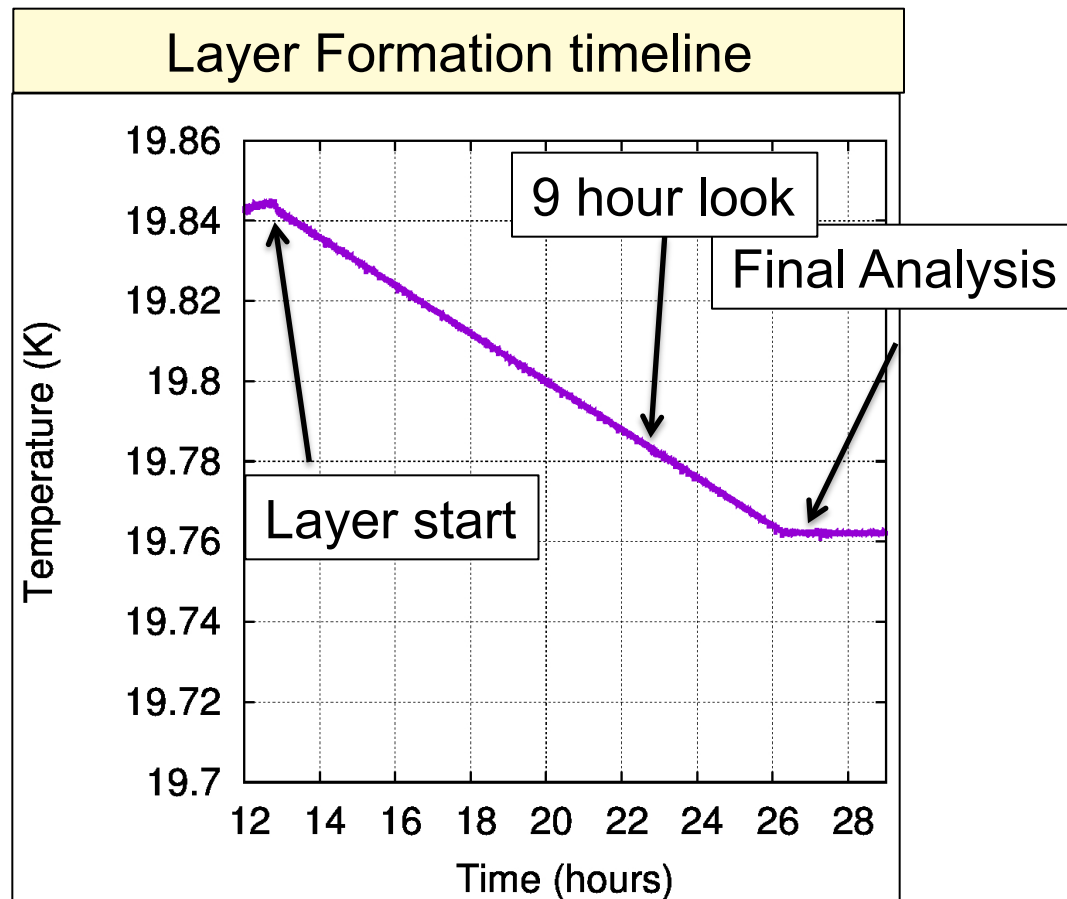
The layer outcome is reliably predicted starting at 9 hours into the 13 hour script

Good layers incorrectly thrown out

Correct outcomes predicted

Bad layers incorrectly allowed to continue growing
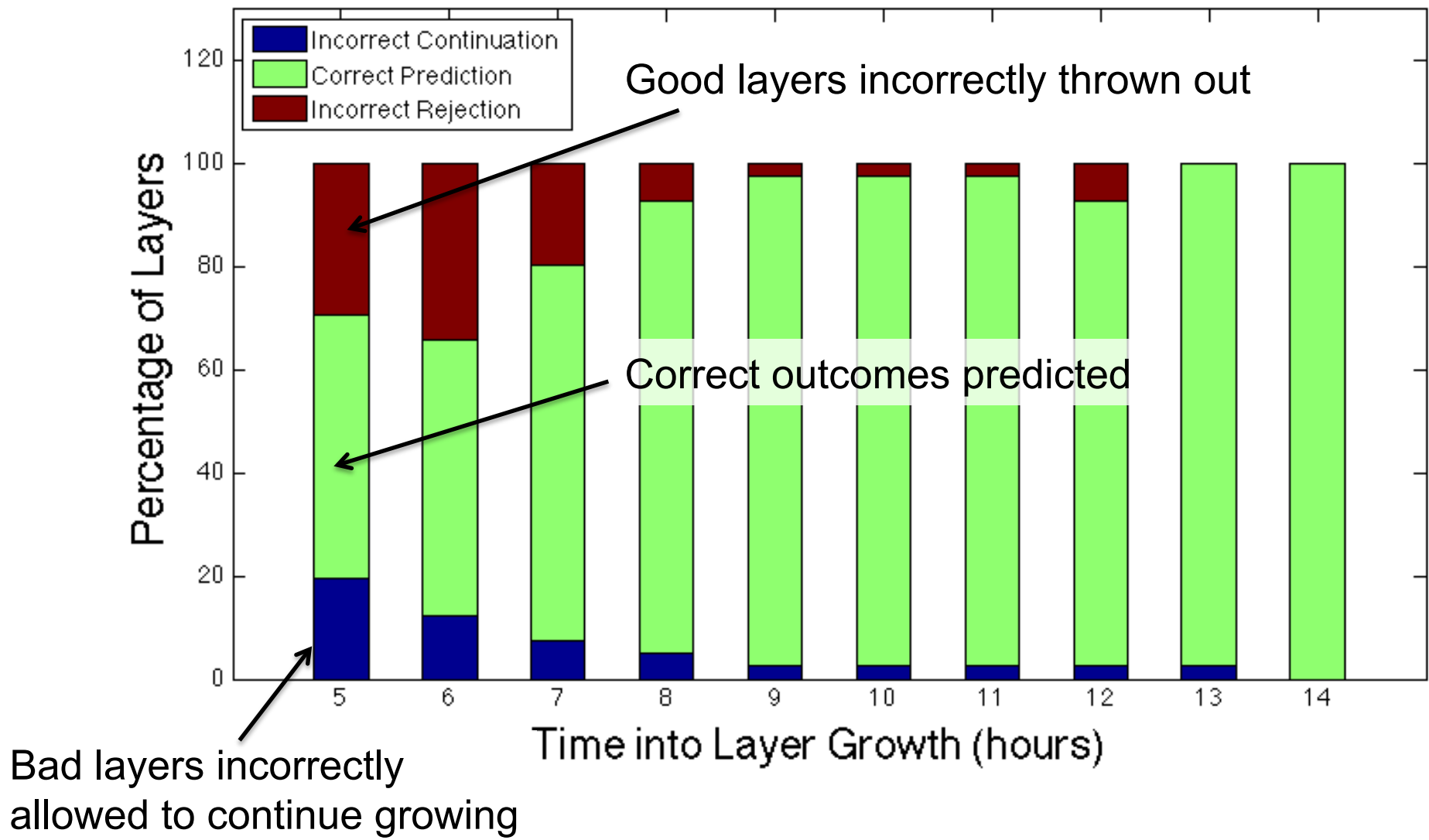
- High cost to incorrectly throwing out good layers since the mean time to next good layer is 60 hours!

Dashboard view of layer verifies layer evolution is completed with respect to grooves at ~ 9 hours

Time Evolution of Layer

Ice edge at 13.5 hours
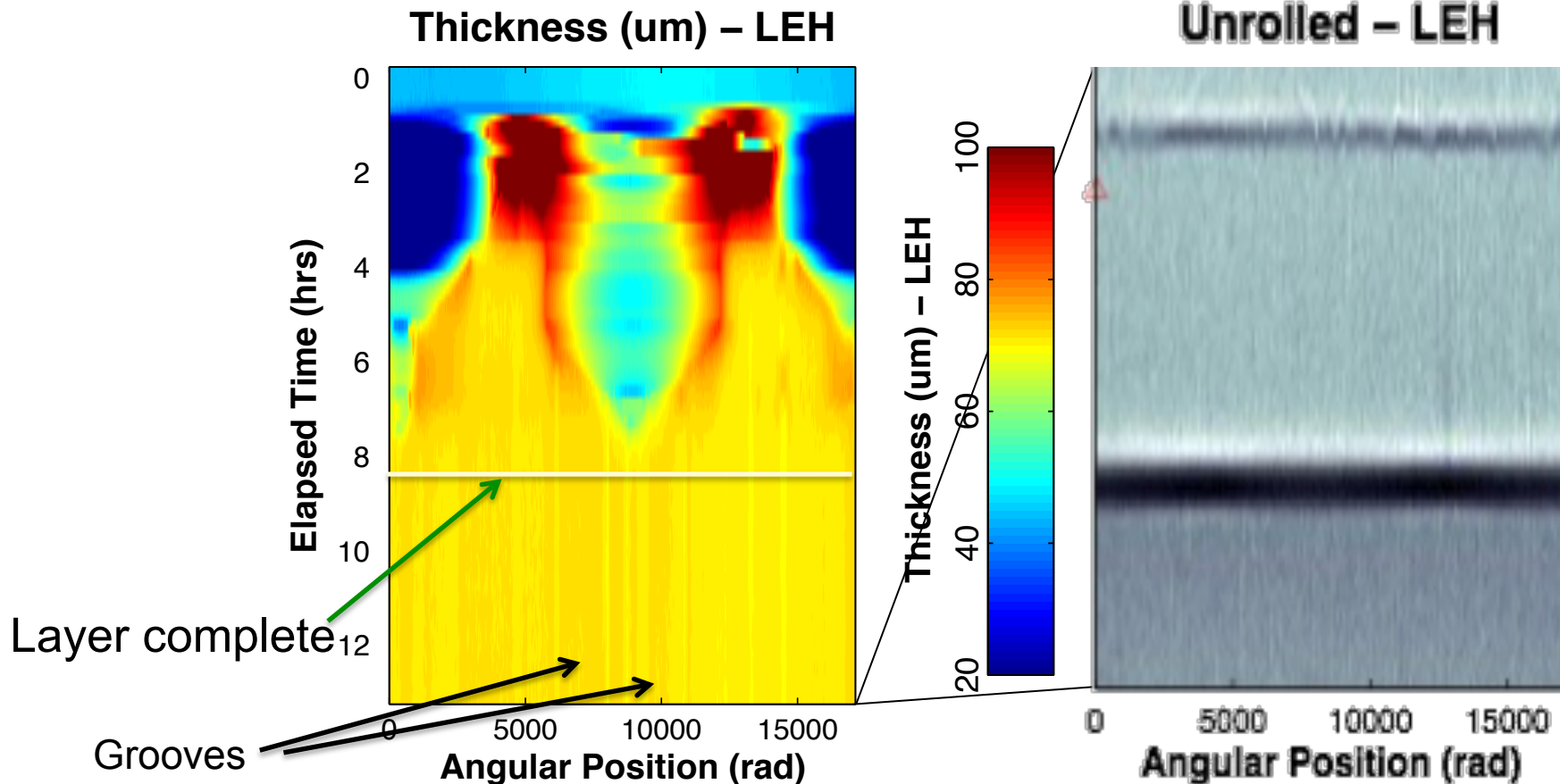
- P1 and P2 continue to change between hours 9 and 13
- Occasionally layers are still moving between hours 9 and 11, dashboard will show that evolution

Layer will be analyzed at 9 hours and evaluated with respect to rules of engagement going forward

Time Evolution of Layer
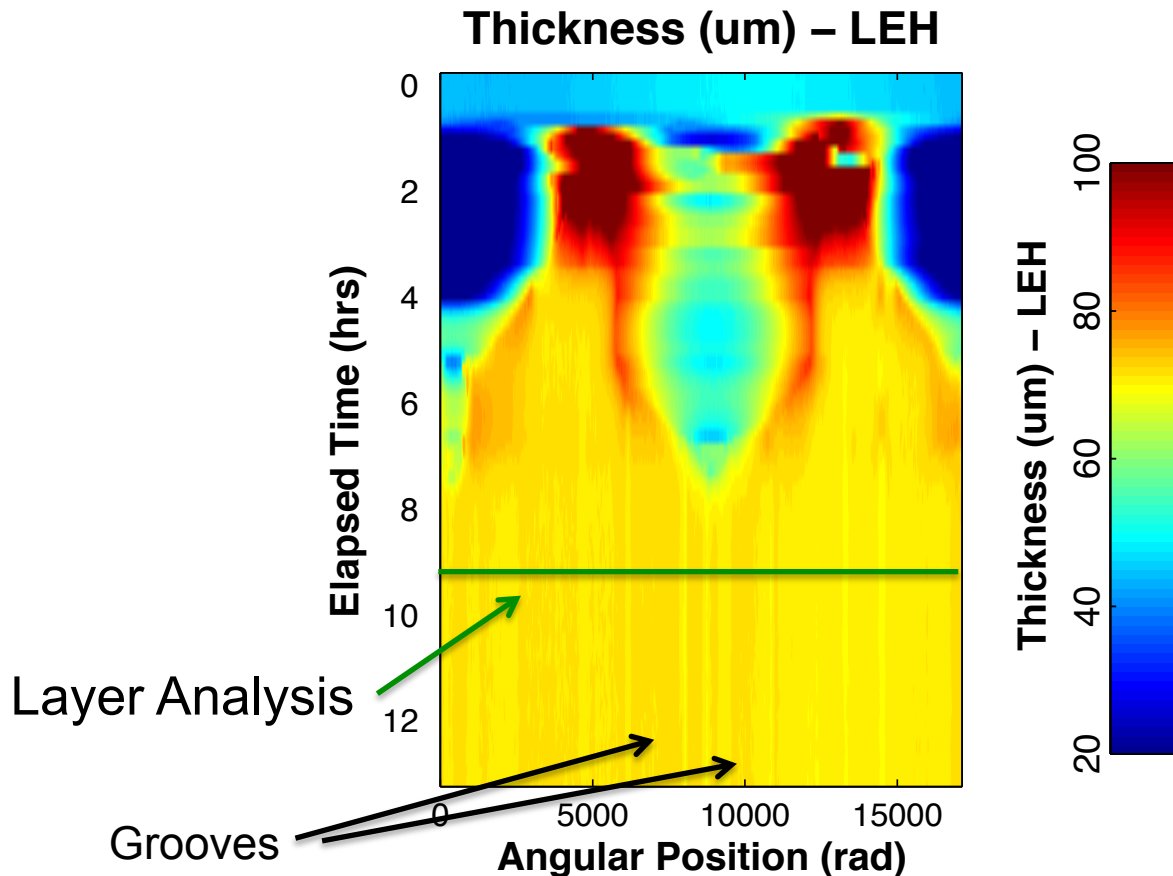
- No early aborts before 9 hours, except lost seeds (at 45 min mark)
- NIF staff will run standard layer analysis at 9 hours, send report to shot RI
- Shot RI decides fate of layer
  - Default action of facility will be to continue until end
- Another report at end of layer will be compared to ROE. Facility will act based on ROE

Probability of a layer being accepted[*] is 23% per attempt

- **Data fits geometric distribution** *showing attempts are independent*
- **94% of shots require < 10 attempts**
- **Average time to accepted layer is 61 +- 30 hours (2013-2015)**
- **It is vital to make as many attempts as possible in a given time period**
- **Must identify bad layers as early as possible in layering attempt**

- **[*]Accepted layer does not always mean desired layer**
- **Only ~10% of layers are "ignition quality", ~ 20% are near-ignition quality**
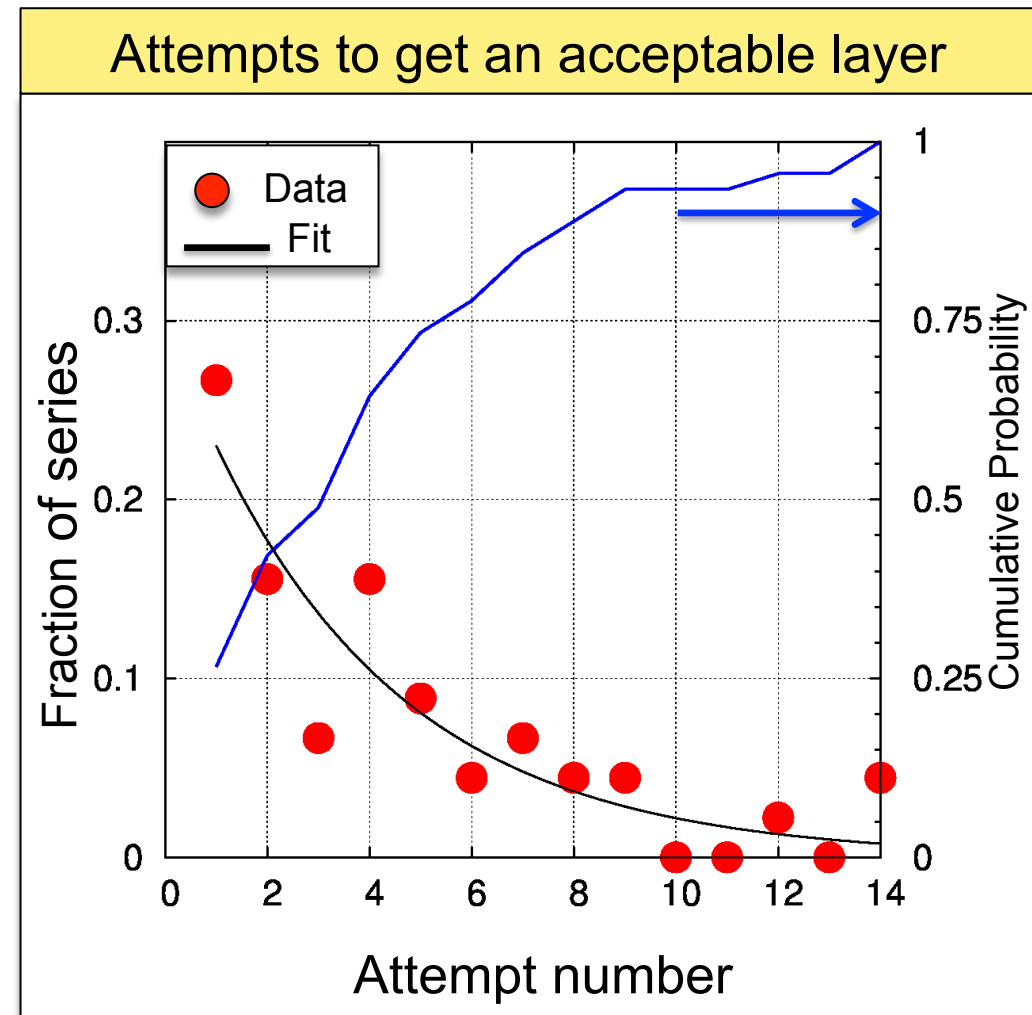
Attempts to get an acceptable layer

Is there enough time for another attempt? Typical timeline is ~39 hours from attempt start to shot
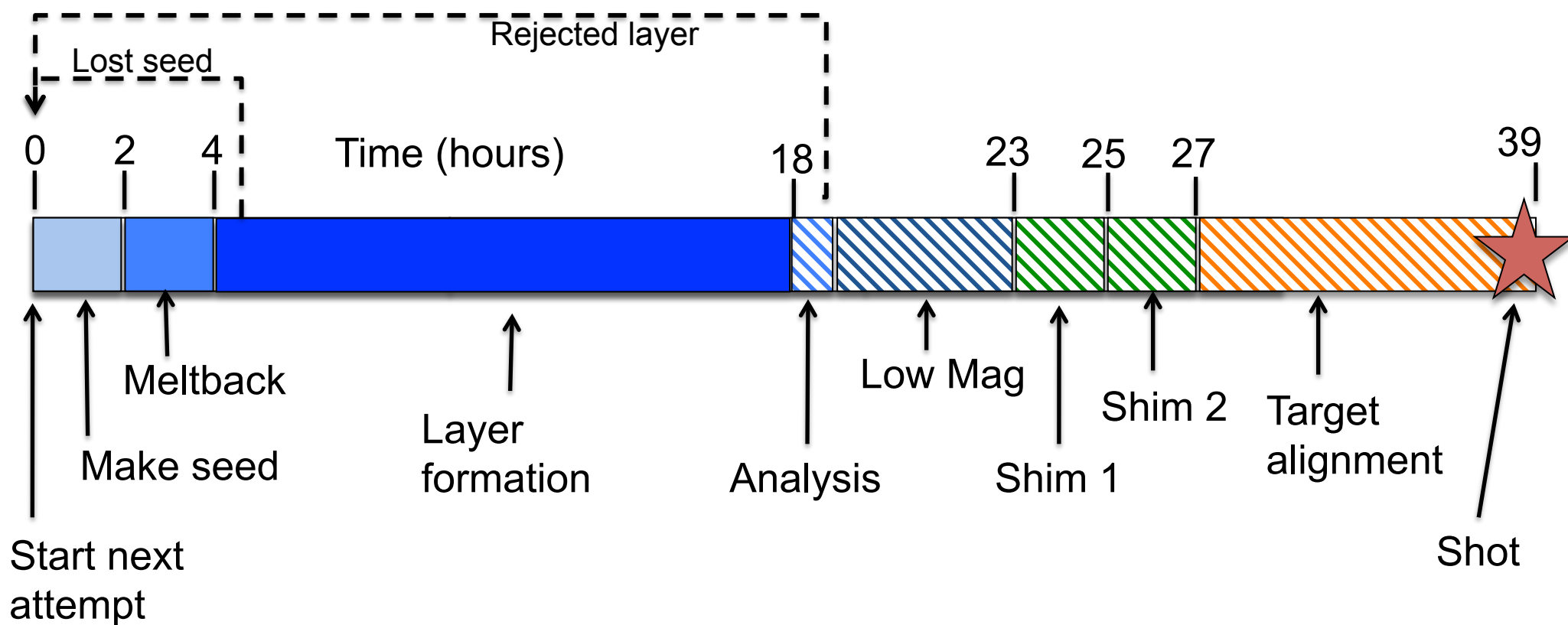
- Verify no planned ICCS restarts during (Add 2-3 hours if planned)
- Assumes target bay access available to setup for low mag and switch back to standard imaging for shimming
- Assumes seed successfully preserved in Meltback (see next slide)
- Length of timeline can be affected by Facility activities and staff availability – Be sure to ask Shot Director or Field Engineer for potential delays!

Lost seed costs 5-6 hours
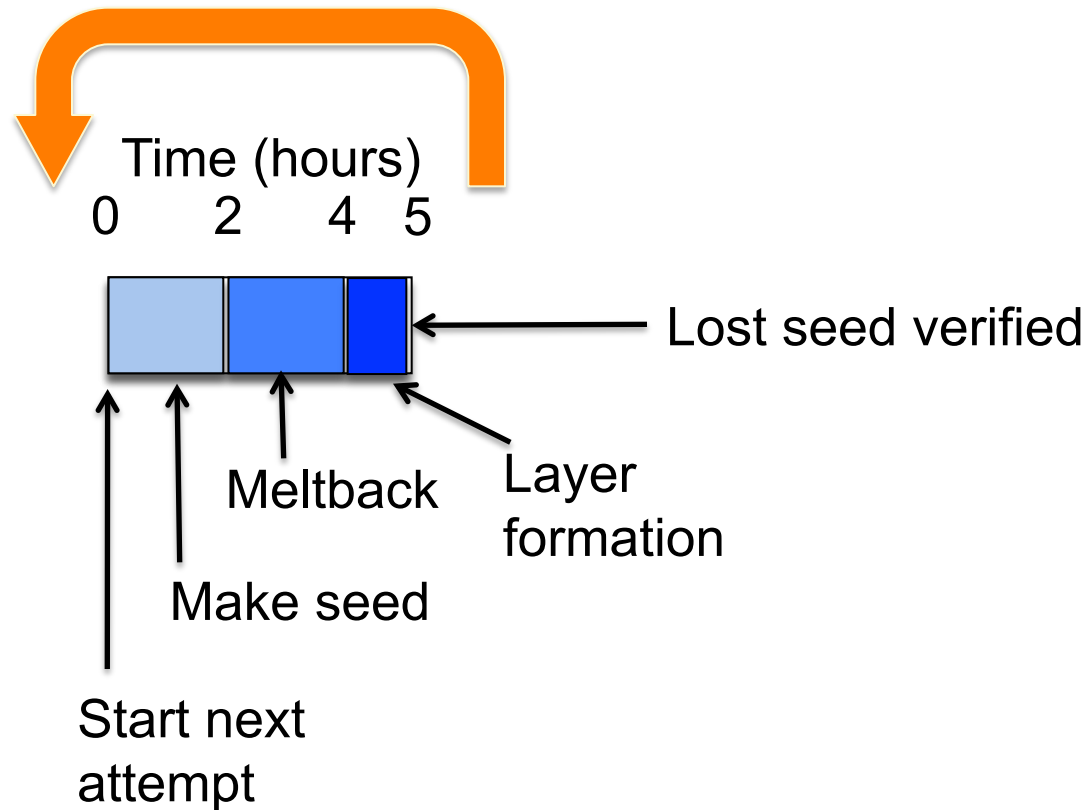
- Restart next attempt at MakeSeed, increasing allowed amount of remaining solid if appropriate
- Lost seeds *usually* occur when fuel is > 100 hours old, when melting becomes faster

4 Day layer timeline allows for 2-3 layer attempts
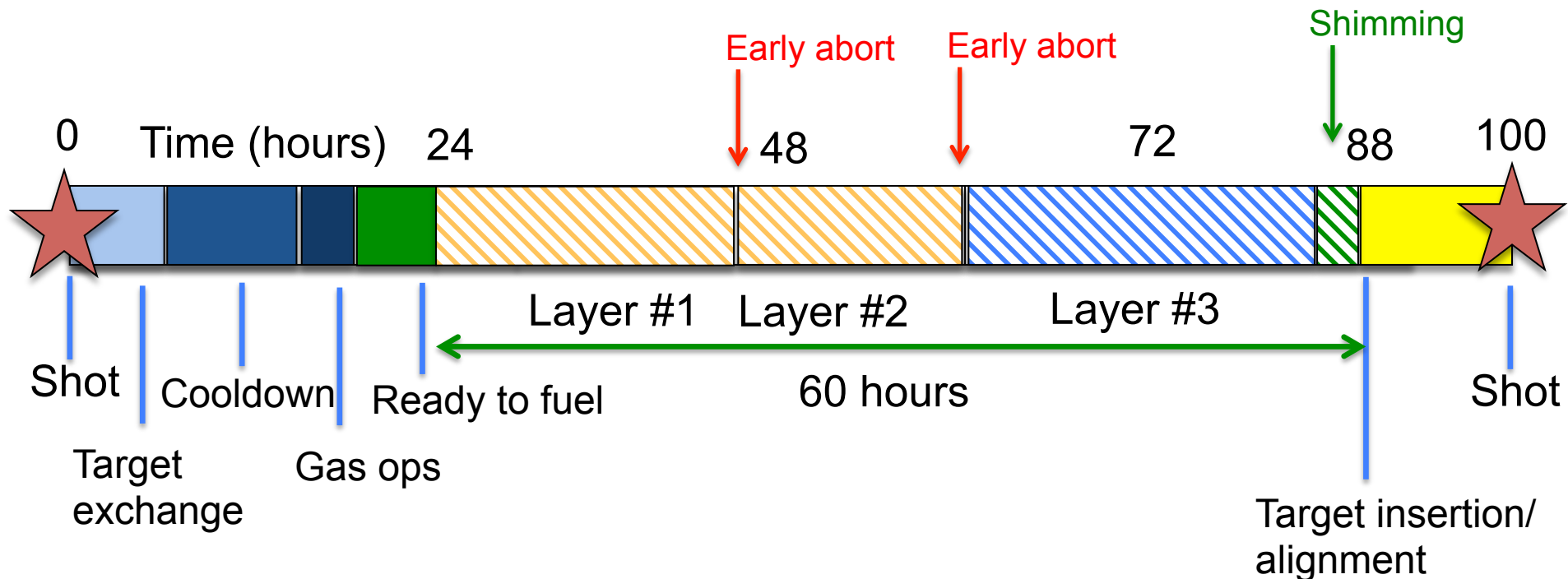
- Typically 22-25 hours from previous shot to fuel loading of target
- 1st layer attempt is usually 24 hours to completion after fuel loading
- Additional full attempts require ~ 18 hours for complete layer
- About 50% chance of getting acceptable layer in 60 hours of "Layering", 84 hours from the last shot
- 7 Day layers allow another ~ 60-65 hours, total layering time ~ 120 hours

Notional Timeline for "4-day" layers

Friday 10/30				Saturday 10/31				Sunday 11/1						Monday 11/2					
12:00 AM	7:00 AM	12:00 PM	7:00 PM	12:00 AM	7:00 AM	12:00 PM	7:00 PM	12:00 AM	7:00 AM	12:00 PM	6:00 PM	7:00 PM	9:00 PM	12:00 AM	3:00 AM	7:00 AM	12:00 PM	4:00 PM	7:00 PM

Begin install

Begin Fueling

Preflight/makeSeed, etc

1st layer starts

Reject first layer (12 hours)

Begin 2nd layer

2nd layer starts

2nd layer completed

Shim Correction

2nd Shim Correction

Reject first layer (12 hours)

Begin 2nd layer

2nd layer starts

Reject 2nd layer early (9 hours)

Begin 3rd layer

3rd layer start

3rd layer complete

Shim correction

Shim Con

Target needed

Relative location of the three x-ray imaging systems: Top view

Imaging coordinates
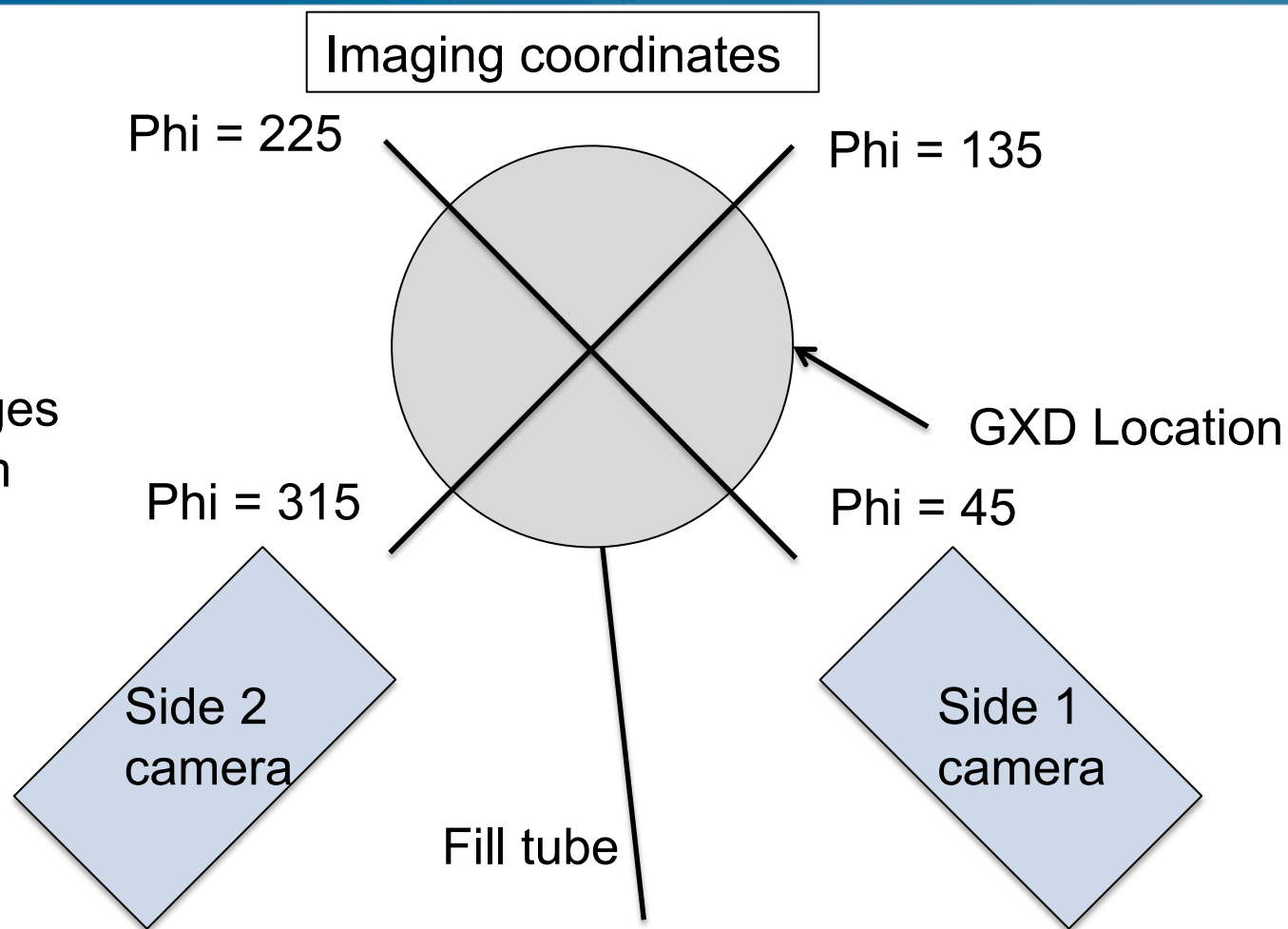
Phi = 225

Phi = 135

This is viewed from above.

Sides 1&2 images are viewed from camera perspectives.

GXD Location

Phi = 315

Phi = 45

Side 2 camera

Side 1 camera

Fill tube

Cryotarpos Door

Side 1 sees : Phi135 and Phi315
Side 2 sees : Phi45 and Phi225
GXD projects into Phi135 view
Add 15 degrees to get to Target Chamber coordinates

LEH view is looking up from below, phi angles are flipped left/right (CryoTarpos image coordinates)
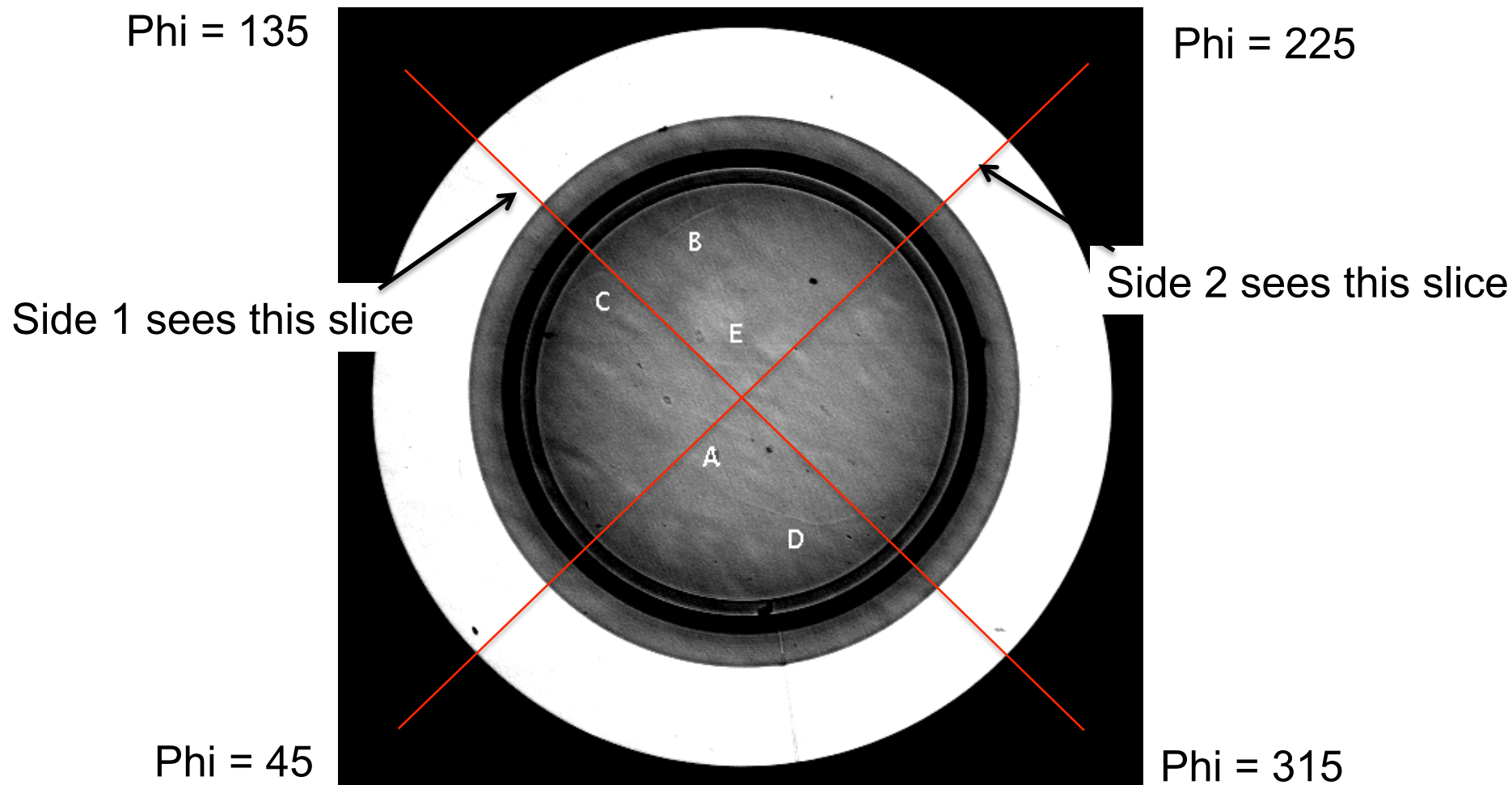
Phi = 135

Phi = 225

Side 1 sees this slice

Side 2 sees this slice

Phi = 45

Phi = 315

Side 1 sees : Phi135 and Phi315
Side 2 sees : Phi45 and Phi225
GXD projects into Phi135 view
Add 15 degrees to get to Target Chamber coordinates

Three views of fuel surfaces are characterized for shape, roughness and process monitoring

Side view (x2)	LEH view	Unwrapped LEH view

Side view (x2):
Layer char. "starburst"

Slot to view liquid

LEH view:
θ

r

r

Unwrapped LEH view:
Fuel edge

$h(\theta, t=12\ \text{hours})$

Capsule edge

θ

Groove at D-T surface

Groove depth

69 µm
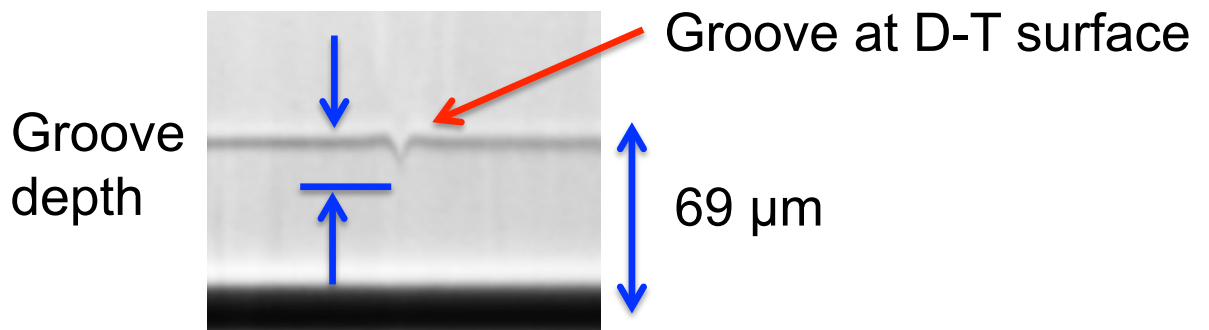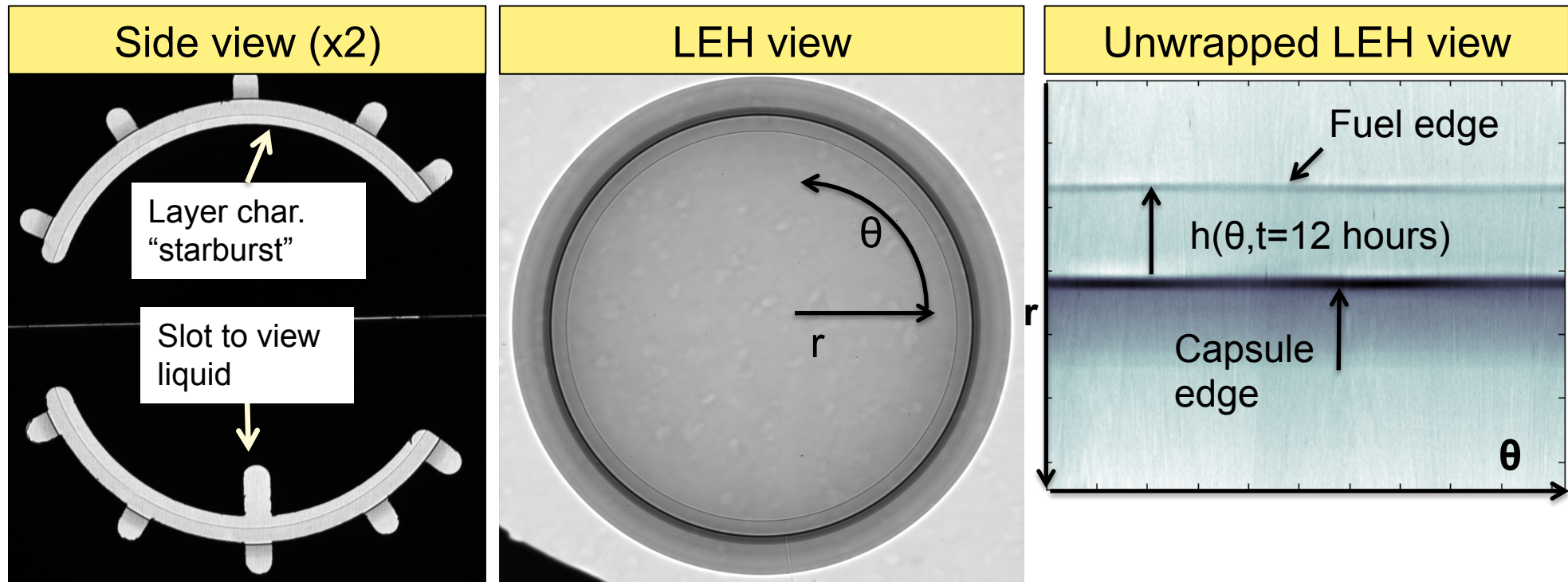
Images are unrolled for mode analysis, groove measurement
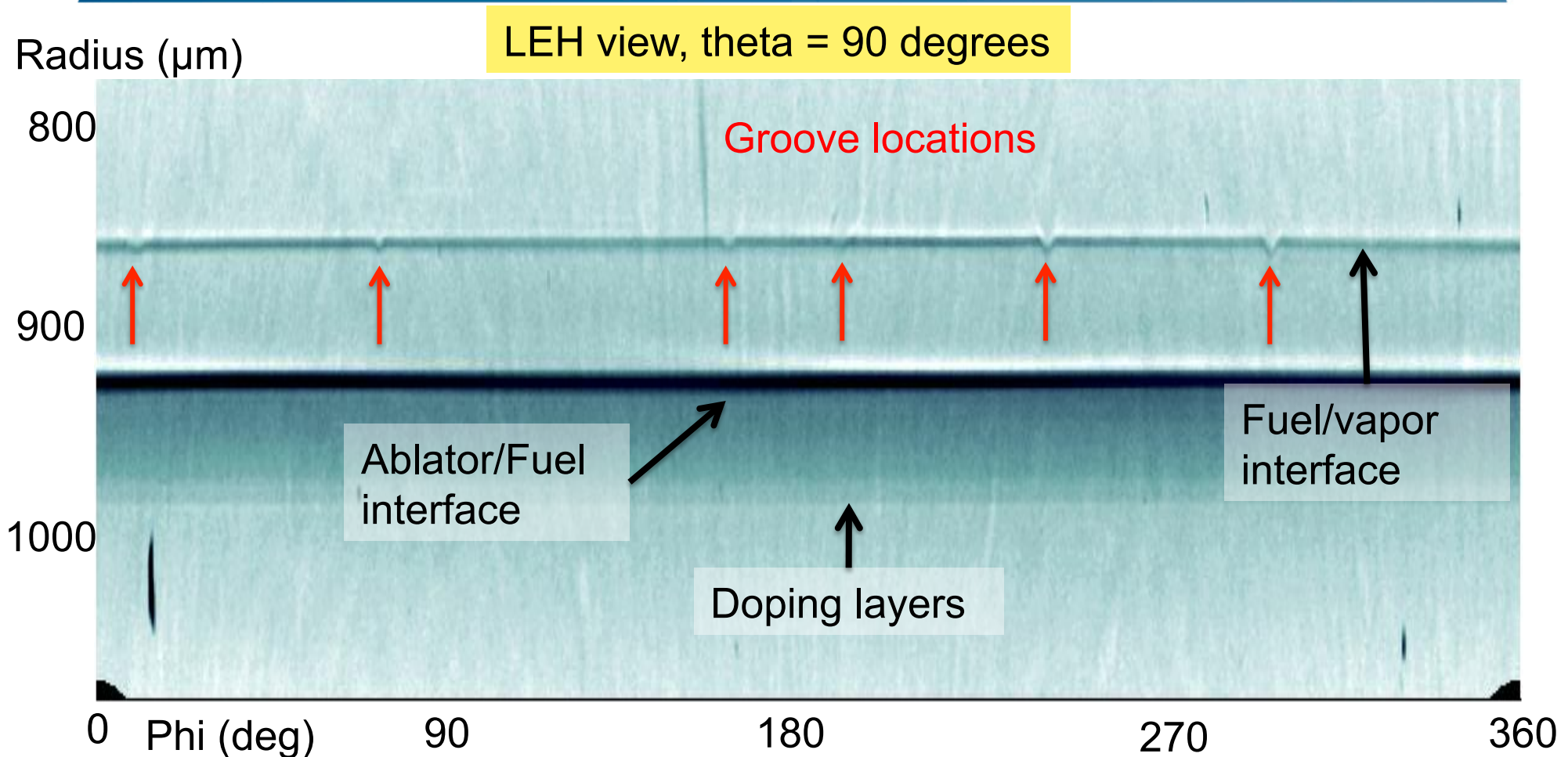
- Groove detection is via automated feature detection. Human verifies and removes false detections
- Pixel size is not square in unwrapped images – Radius is stretched, angle compressed

Grooves, fourier modes measured in the unwrapped images
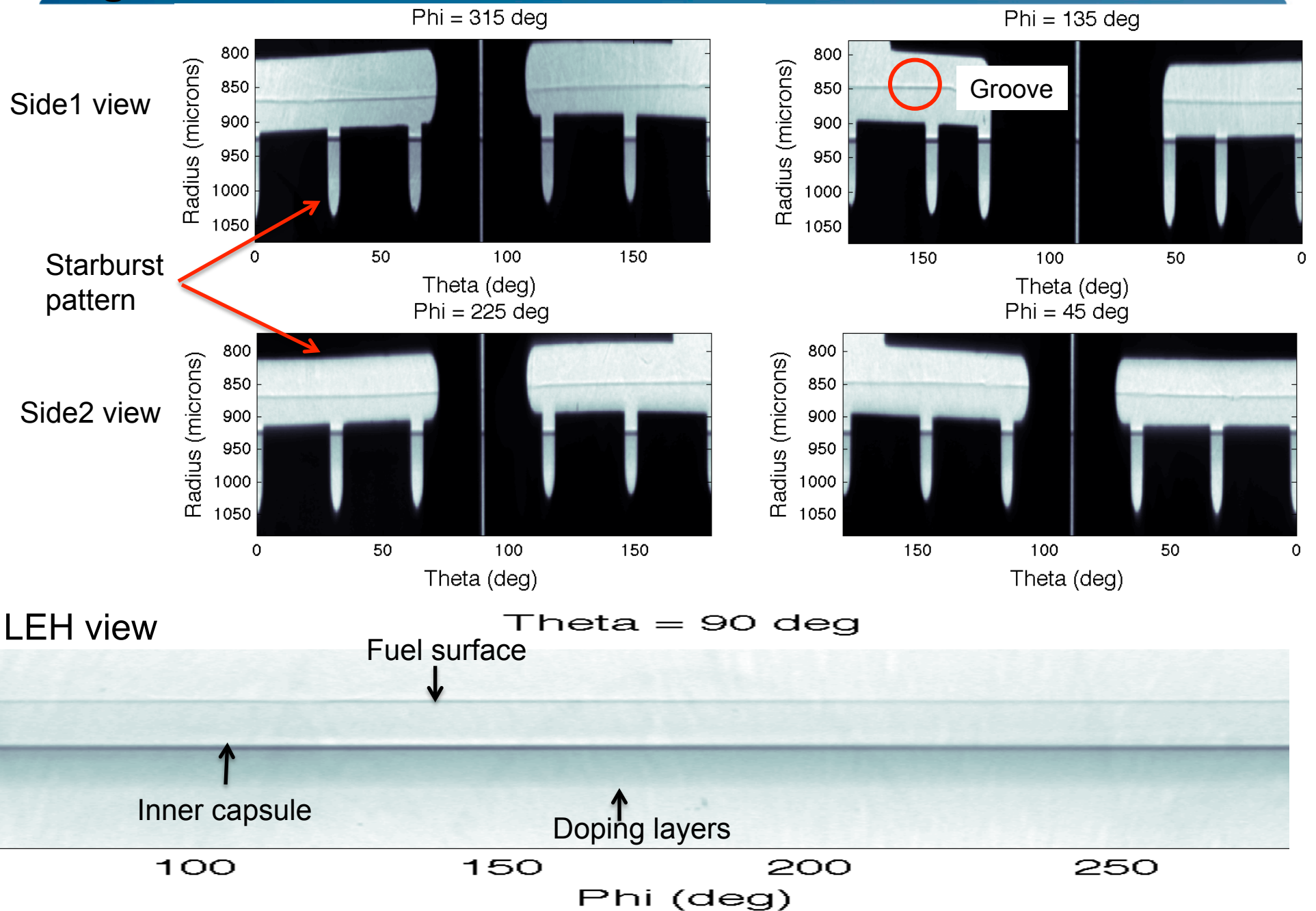
Side1 view

Starburst pattern

Side2 view

Phi = 315 deg

Phi = 135 deg

Groove

Phi = 225 deg

Phi = 45 deg

LEH view

Theta = 90 deg

Fuel surface

Inner capsule

Doping layers

Defects are classified as standard and non-standard

- **Standard defects appear to be grain boundary grooves**
- **Non-standard defects include "mountains"**
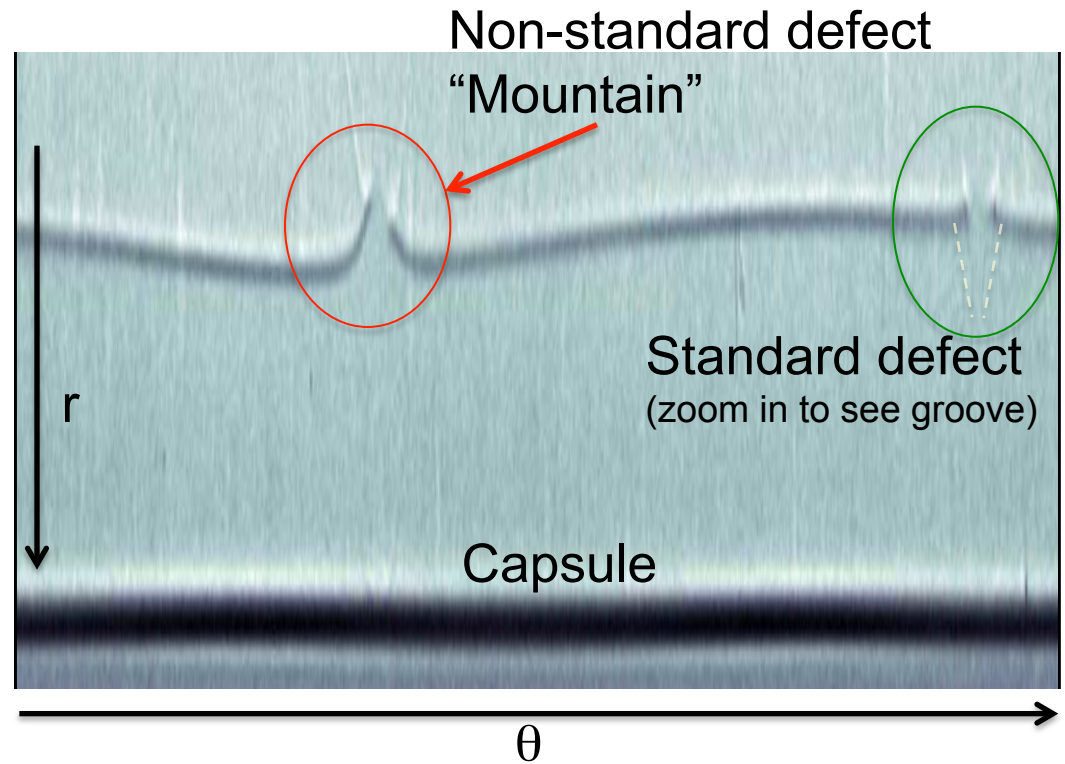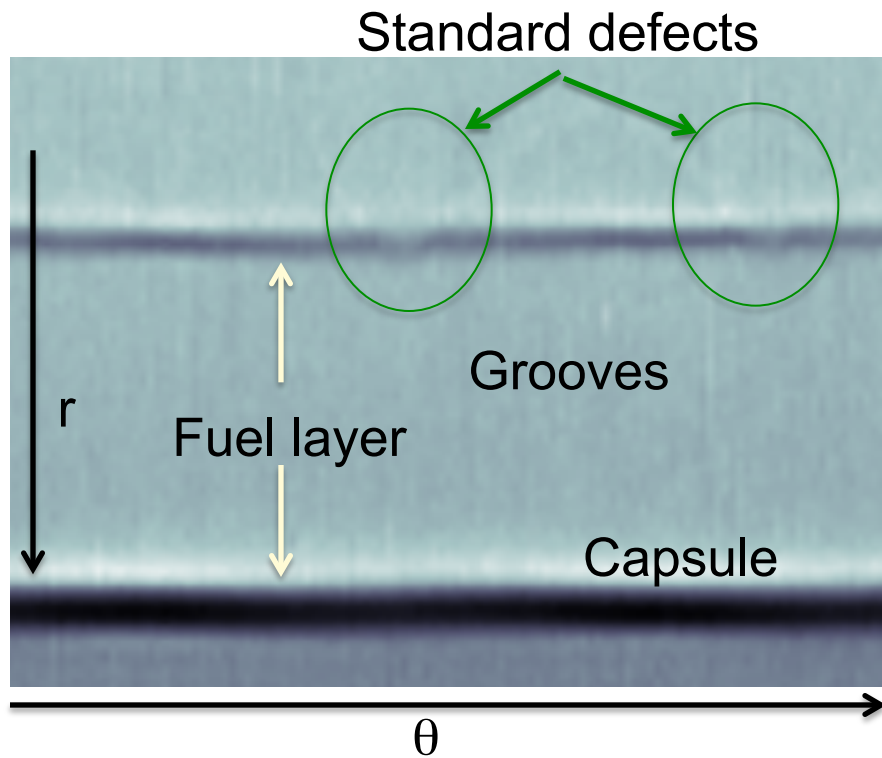
K is estimated by connecting measured grooves in three x-ray views with Monte Carlo model

Model input

x-ray views

grooves

+ Low Mag →

Reported layer quality

Legend:
- D < 6
- D < 10
- All

Y-axis: K (µm) — 0, 0.25, 0.5, 0.75, 1, 1.25, 1.5

X-axis: Total detected groove depth (µm) — 0, 5, 10, 15, 20, 25, 30
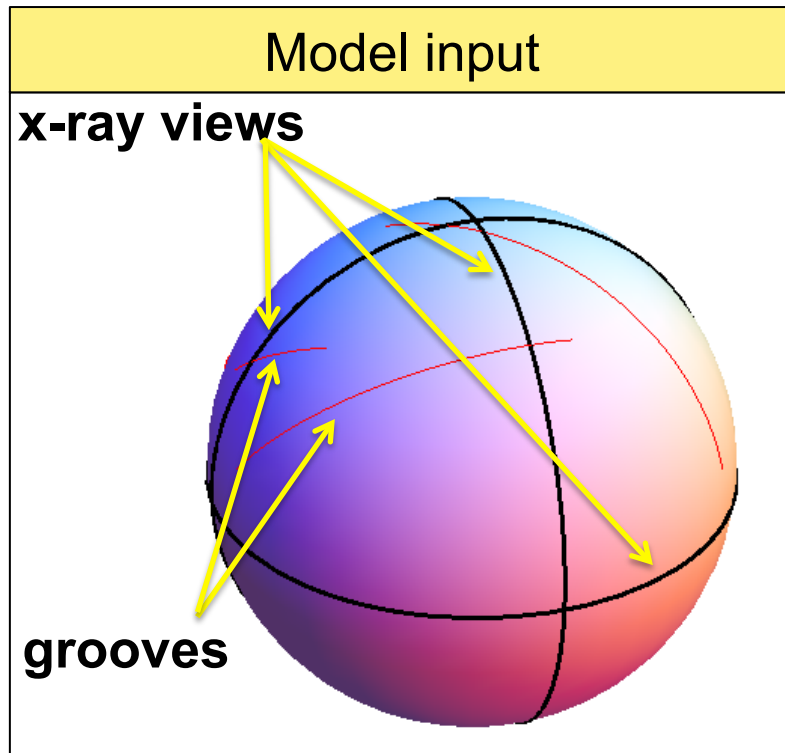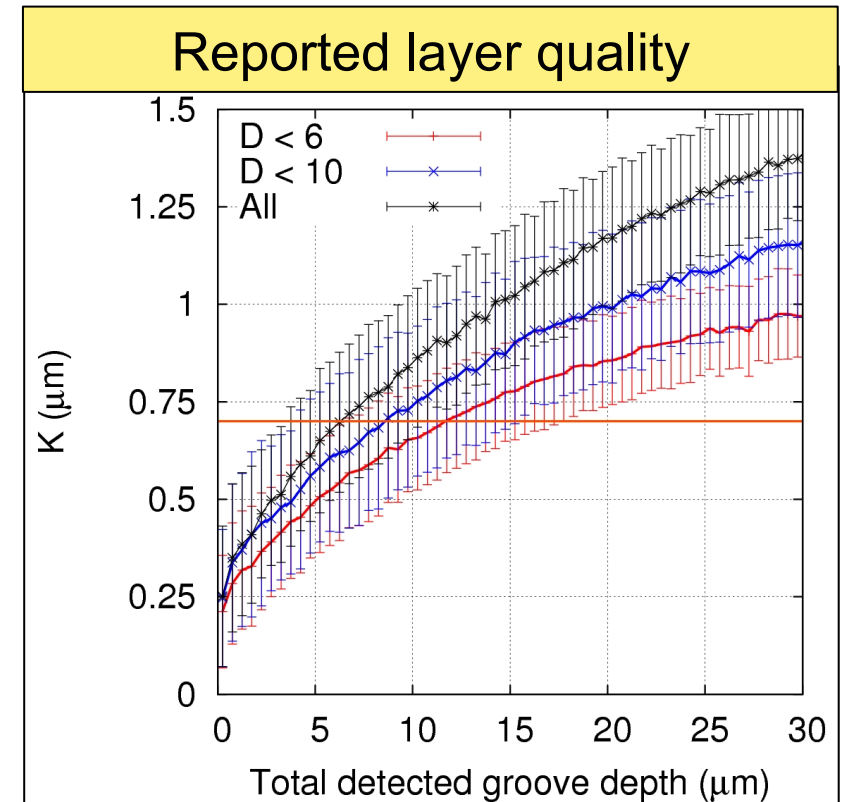
- **Detect grooves and sum their depths in three views, then derive K from Monte Carlo based on off-line interferometer data**

- **Refine K based on maximum groove depth, D, from Low Mag + 3 views**

K > = 1.0 µm is unlikely for grooves <=4 microns deep

- $L = K^2 \cdot V / A^2$, L = groove length, A = area, V = volume

Total groove length (microns) vs K and Depth				
K(µm)	Depth (µm)	2	3	4	5
0.5		21,000	9,300	5,220	3,360
0.7		41,100	18,300	10,230	6,580
1.0		84,000	37,300	20,800	13,400

- **2,000 µm long groove is almost certain to be detected in limb views**
- **Should see ~ 10 grooves 4 µm deep to reach K = 1.0 µm**
- **Monte-Carlo calculation assumes all possible grooves on the capsule surface, but we can exclude largest with low mag images**

Low-Mag Layer Analysis

- **Low mag imaging is a screening tool to look for large, short defects that would be missed in the three x-ray views (80% of surface area vs 30% in three limb views).**

- **Signal to noise increase by averaging 900 images (~3 hours)**

- **Contrast of feature is used to estimate depth**

- **Only translate contrast to depth for 'groove' shape, other shapes will result in different contrast**

- **Cannot tell from LEH view alone if groove is on upper or lower hemisphere of shell**
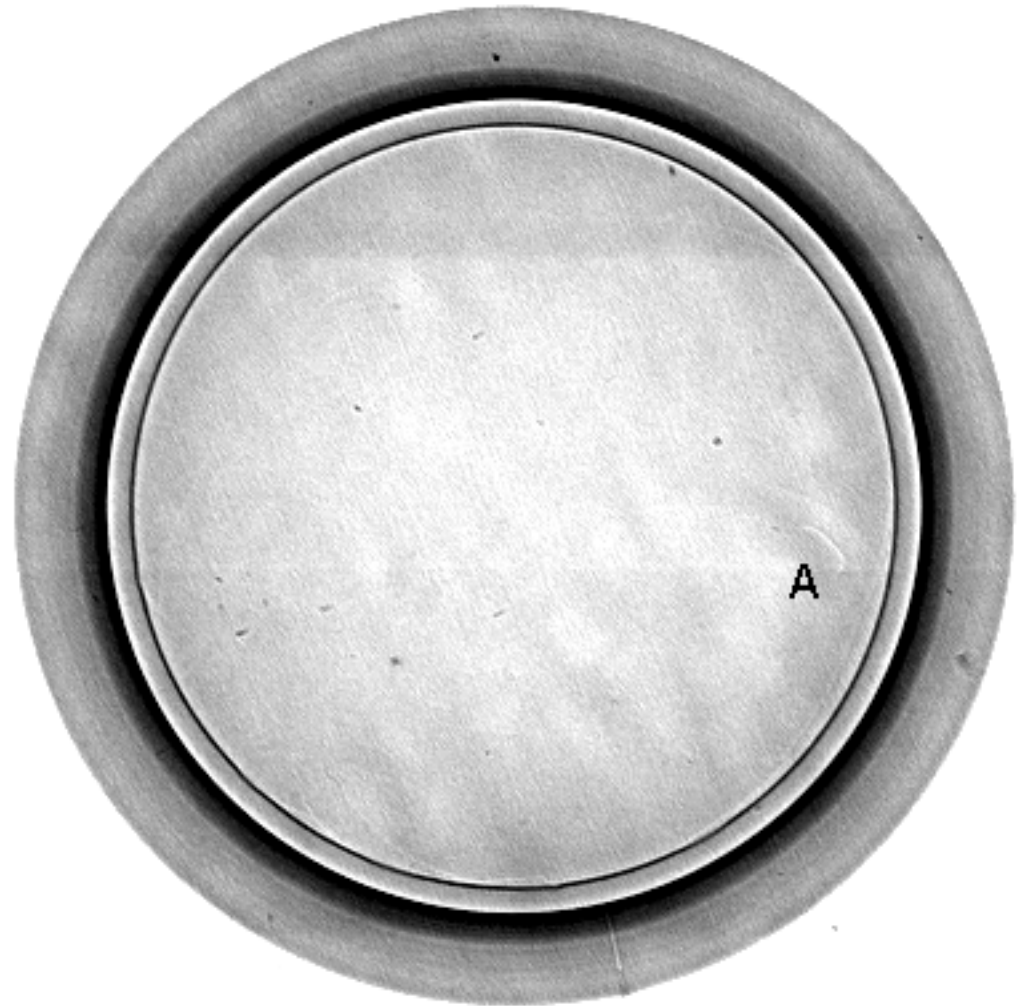
Order and number of shimming adjustments vary with target history

ITPS & B581 thermal environments are not identical

Layer in ITPS?

yes → Start with ITPS params

no → Use best guess params

Make first estimate of P1 after set inventory completes. Adjust if > 5 µm P1

Grow layer, attempt N

N = N + 1

Refine shim, if possible

Is layer accepted for grooves?

yes → Refine shim, if needed

no →

Low Mag → Hold for Shot
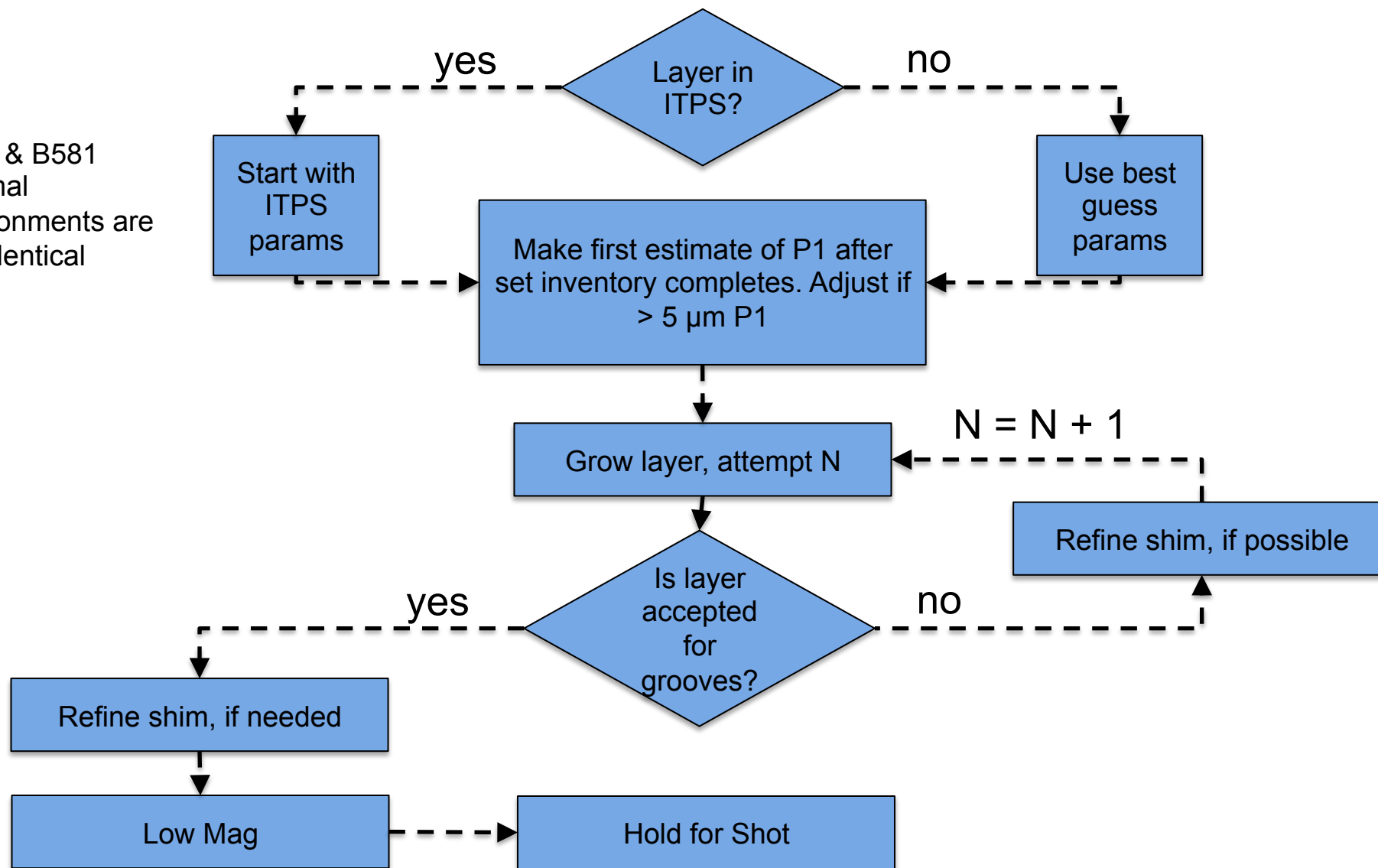
P1 shimming is accomplished by offsetting the temperatures at either end of the hohlraum

SIDE VIEWS

Top

Bottom

P1 = 0

P1 with both sin & cos componentts

P1 sin (shimmable)

P1 cos (unshimmable)

LEH VIEW

P1 = 0

P1 with both sin & cos componentts

P1 sin (shimmable if target is equipped with M1 heater and ice is thick opposite fill tube)

P1 cos (unshimmable)

Define ΔT = Top - Bottom
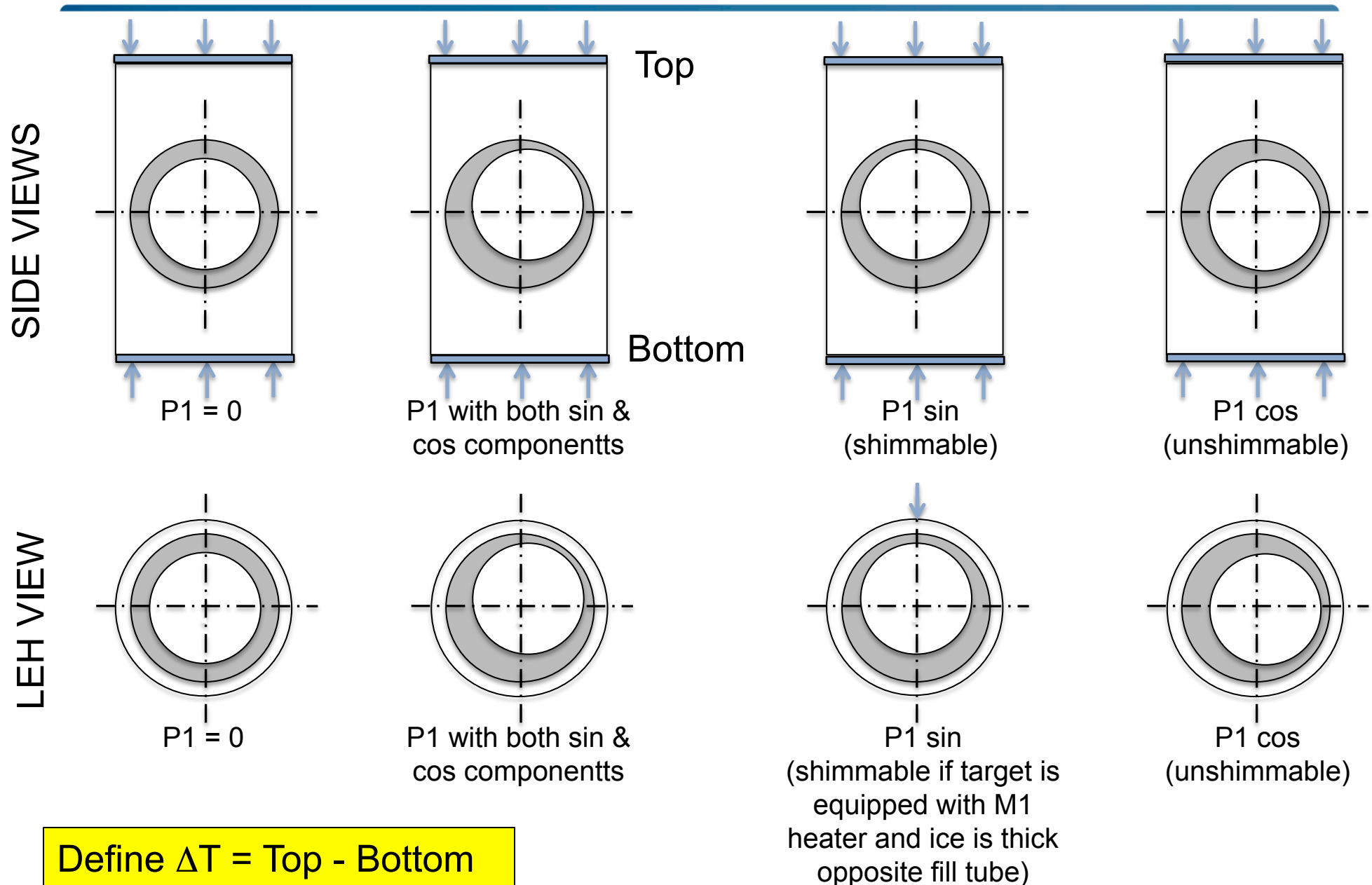
P2 shimming is accomplished by applying a radially symmetric current at one or two points along the hohlraum

SIDE VIEWS

P2 = 0 | P2 with both sin & cos components | P2 cos (shimmable) | P2 sin (unshimmable)

LEH VIEW

P2 = 0 | P2 with both sin & cos components | P2 cos (unshimmable) | P2 sin (unshimmable)
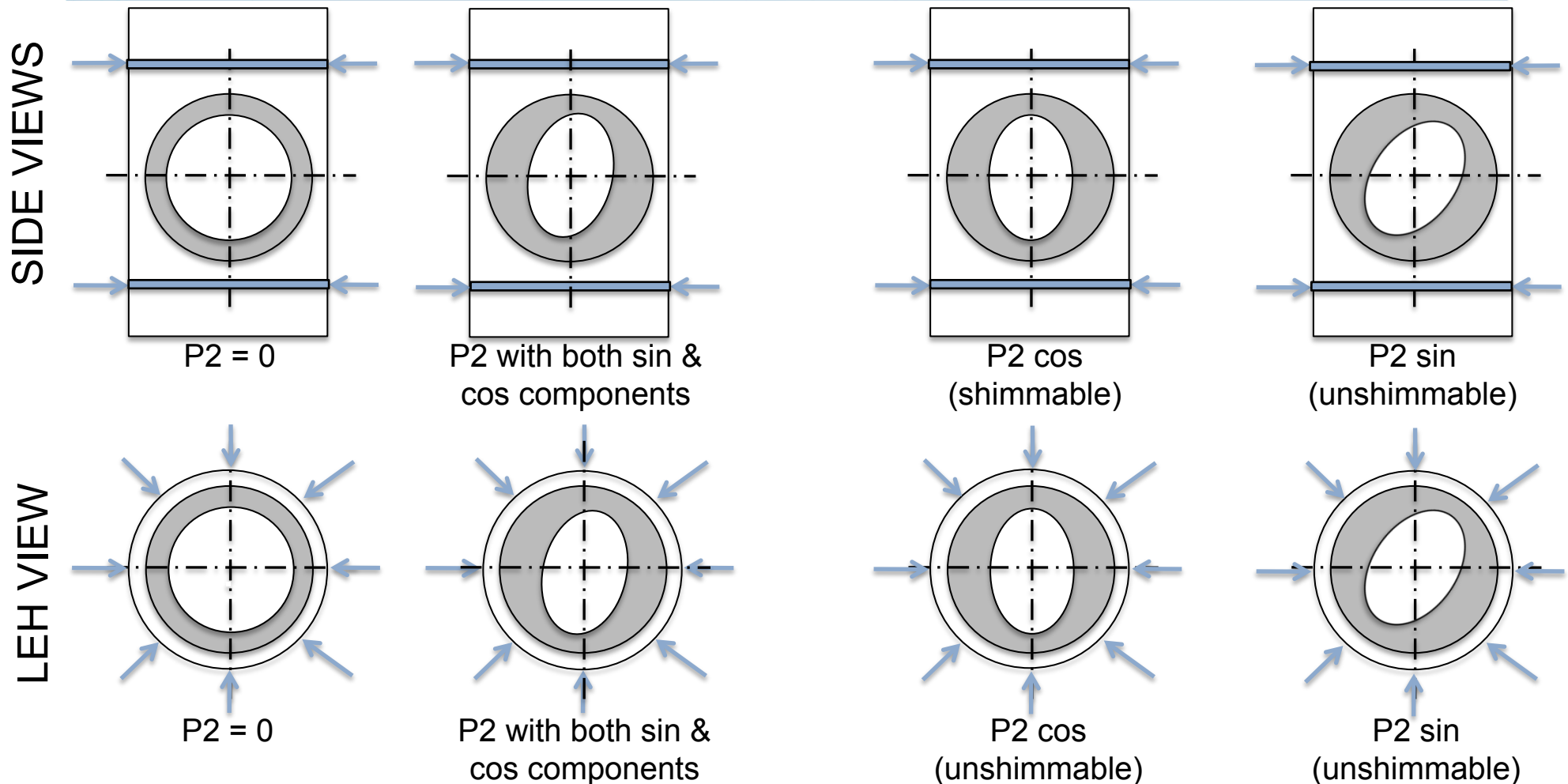
- Layer is thick at the equator if no shim heat is applied. We call this a negative P2
- Positive P2 results from too much shim power, layer is thin at equator

Convection increases with increasing He gas density, resulting in higher odd modes

- **Convective effect scales with He gas density**
- **Model results from Jim Fair, all amplitudes in microns:**

He velocity magnitude vectors

He_density=1.35 g/cc

	cos	sin
P1:	0.00001	1.20133
P2:	-2.44543	0.00000
P3:	0.00008	-0.57207
P4:	-0.08511	0.00001
P5:	0.00003	0.01959
P6:	0.00008	-0.00019
P7:	-0.00003	0.01139
P8:	0.00056	0.00029

He_density=1.6 g/cc

	cos	sin
P1:	-0.00005	1.63379
P2:	-2.45149	-0.00015
P3:	0.00008	-0.80137
P4:	-0.0747	0.00001
P5:	0.000003	0.02775
P6:	0.00172	-0.00001
P7:	0.000003	0.01612
P8:	0.00028	-0.00003

ur, uz

max 4.47

| 4.50 |
| 4.20 |
| 3.90 |
| 3.60 |
| 3.30 |
| 3.00 |
| 2.70 |
| 2.40 |
| 2.10 |
| 1.80 |
| 1.50 |
| 1.20 |
| 0.90 |
| 0.60 |
| 0.30 |
| 0.00 |

min 0.00

Scale = E-4

- **P1 due to convection can be shimmed as normal, P3 cannot**

We found that we get some reduction of P3 by unbalancing shim heater powers

- Convection tends to make bottom of shell warmer, top colder
- Compensate with higher power into top heater, lower power into bottom.
- Adjust TT1-TT3 temperature difference as well.

Current control scheme, top and bottom heater have same power

P2 = 0, P3 ~ -0.9
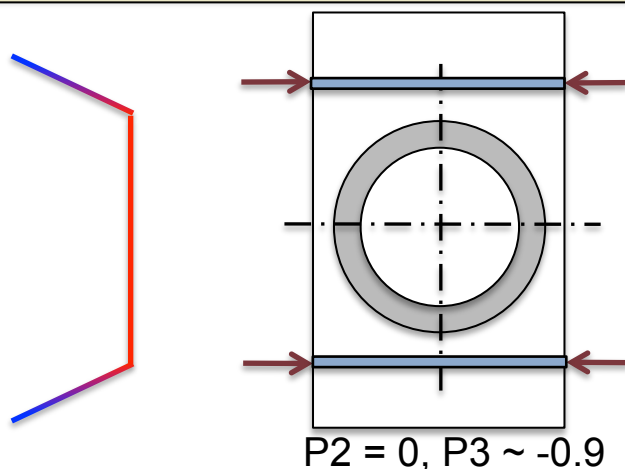
Temperature profile

Proposed control scheme, top heater 2x power, bottom 0x

P2 = 0, P3 = -0.4
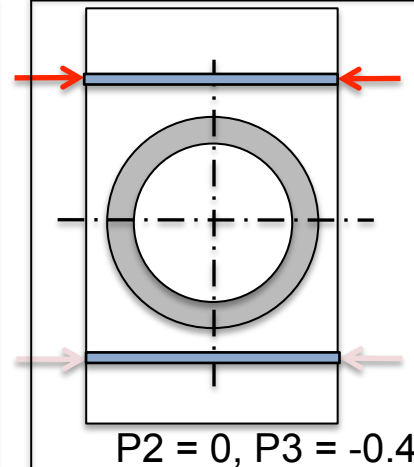
Temperature profile

Nominal vs "P3 control" modes from simulation show reduction in P3 without growth in P2

- Mode amplitudes (microns) with **balanced** shim heaters:
- a1 = 0.878
- a2 = -0.299
- a3 = -0.907
- a4 = 0.0288
- a5 = -0.0067
- a6 = -0.0034
- a7 = 0.045
- a8 = 0.0028

- Mode amplitudes (microns) with **unbalanced** shim heaters:
- a1 = -0.01
- a2 = -0.170
- a3 = -0.483
- a4 = 0.048
- a5 = -0.048
- a6 = -0.007
- a7 = 0.0442
- a8 = 0.0017

- Mode 5 is predicted to grow, but still be within requirement
- Experiment matched simulation, typically observe ~ 0.4 micron decrease in P3 in high foot shots with unbalanced heaters

- There are two challenges with P3 control:
    1. Increased power to one shim heater can drive larger M1
    2. Strong cross-coupling of P2 and P1 shimming

Shimming notes

- P1 shimming is generally uncoupled from other modes; a change in ΔT does not usually change P2, P3.
- A change in shim current can couple to P1
  — Shim P2 can move P1. Amount depends on target, usually < 1 µm
  — P2 is usually within +- 1 micron of 0 during layering, based on previous target types
- A change in shim current can also couple to M1 (The LEH mode 1)
  — Generally M1 amplitude gets higher with increasing shim current
  — Amount is very target dependent
  — Tradeoff is roughly about 1 µm of P2 for 1 µm of M1
- Shim current changes will also change capsule temperature relative to target thermometers
  — About 1 mK/ $1mA^2$ is typical
  — Need to be sure to lower target temperature if shim current is increased after layer has been formed
- If attempting to shim P3, changes in shim current couple 10x more to P1 than P2

Shimming notes (continued)

- **Typical target requires a change of ~ 5 mK in ΔT to change P1 by 1 µm (range is between 4 and 8 for most targets).**
  - **Typical temperature control is about 1 mK, so typically can get P1 to within +- 0.2 µm**
- **Usually avoid adjusting shim currents if within +- 0.3 µm because shim current couples to other modes, target temperature**
- **P1, P2 reported are actually 'Fourier' mode amplitudes, not Legendre modes**

Ignition Quality Layers

C140109-AA-12   K_lowmag = 0.694 um, TGD = 11.3 um, MGA = 146.4 um2

Fuel layer
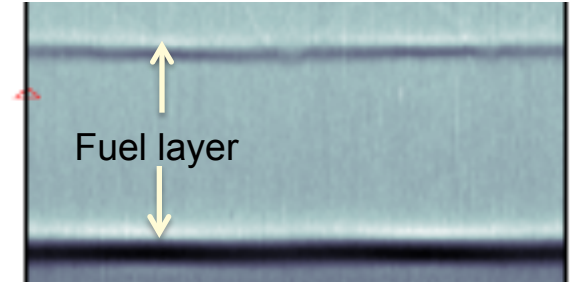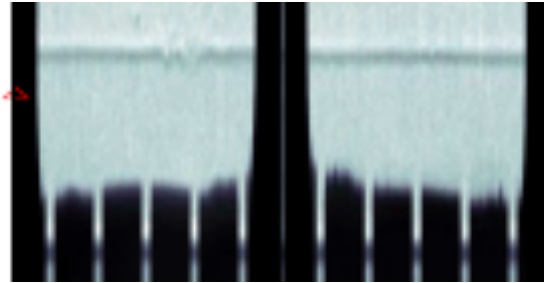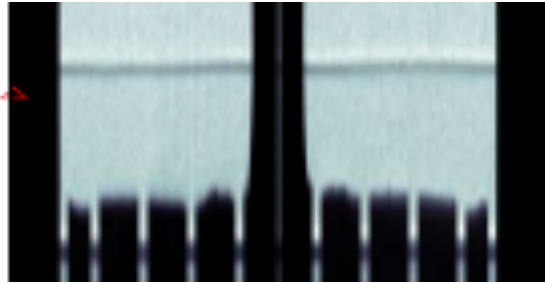
C140128-AA-2   No grooves; K_std = 0.30073 um
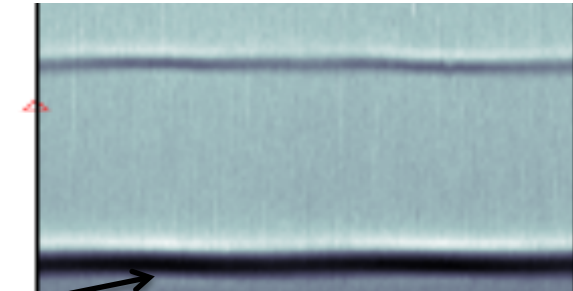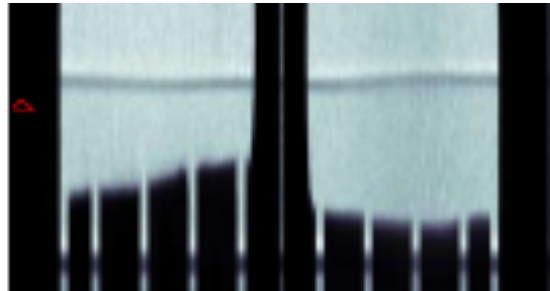
Capsule

C140128-AA-4   No grooves; K_std = 0.30073 um

Tuning quality layers by standard process

C140109-AA-12   K_std = 1.2849 um; 25 um TGD

Fuel layer
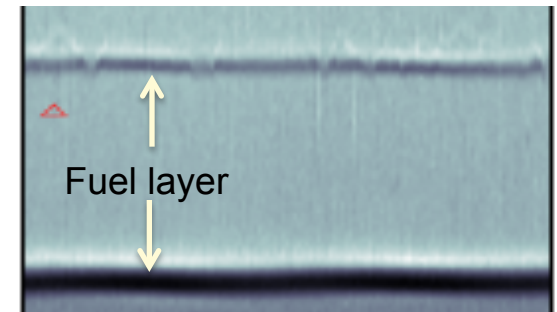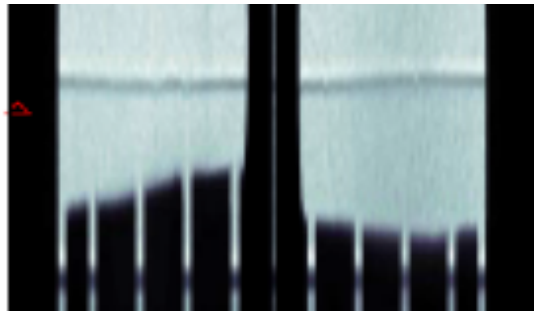
C140128-AA-11   K = 0.99 um, 13.7 um TGD
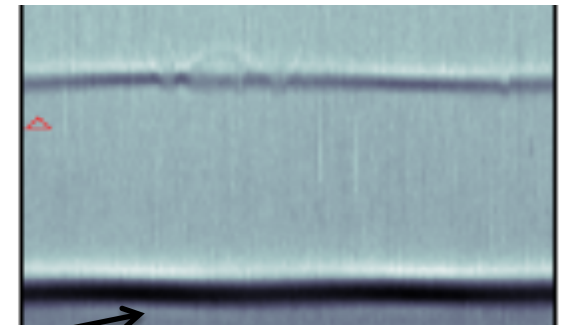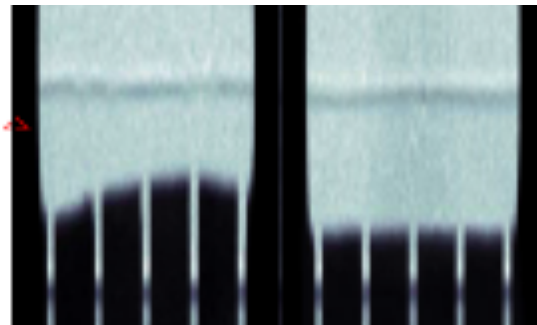
Capsule

C140220-AA-6   K = 1.26, deep defect in low mag
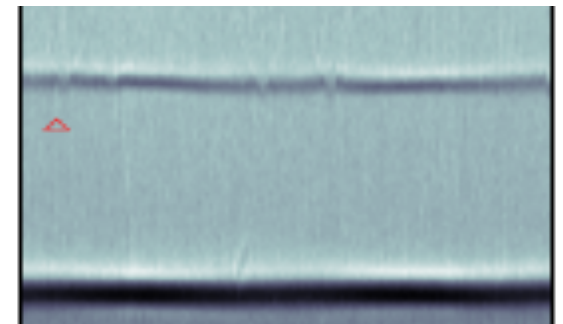
Tuning quality layers by standard process

C140305-AA-1   Aborted for max groove area (450 um2); not yet shimmed
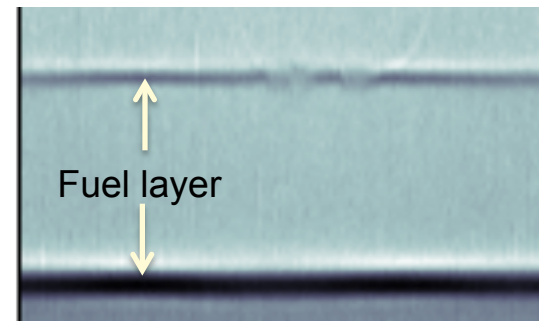
Fuel layer

C140513-AA-1   K = 1.18 um, TGD = 20.2 um
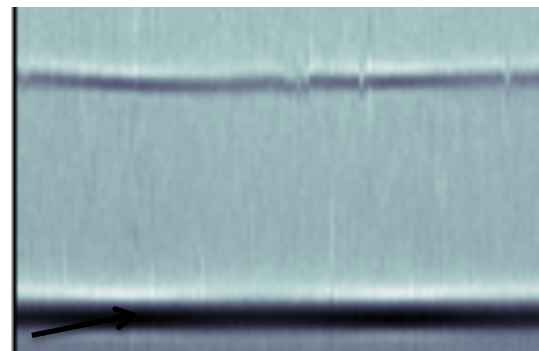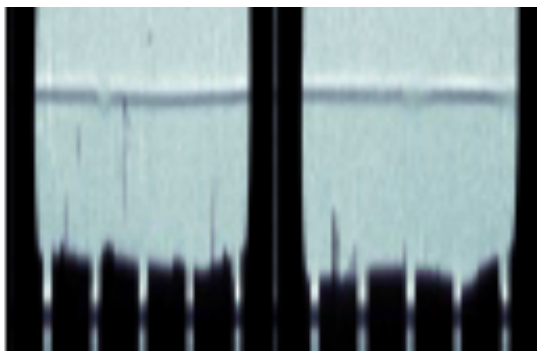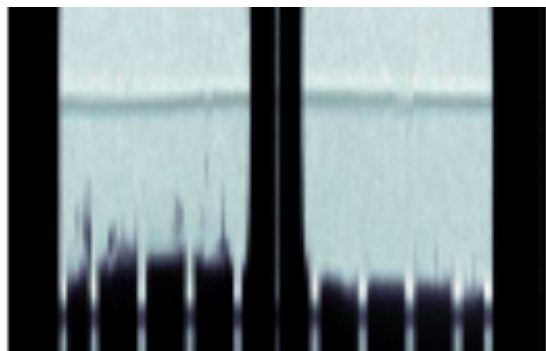
Capsule

C120728-   K =
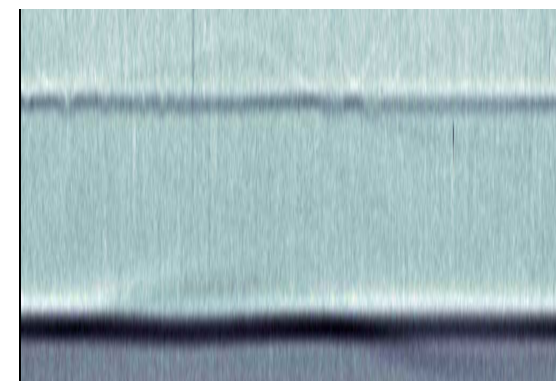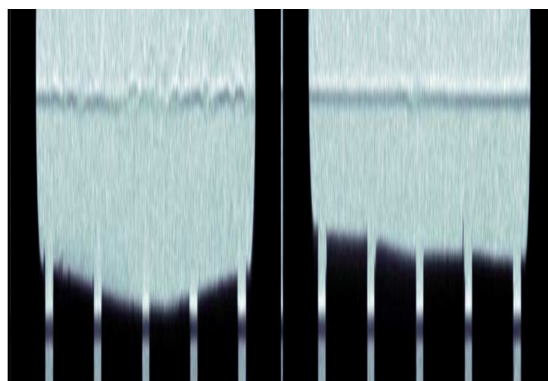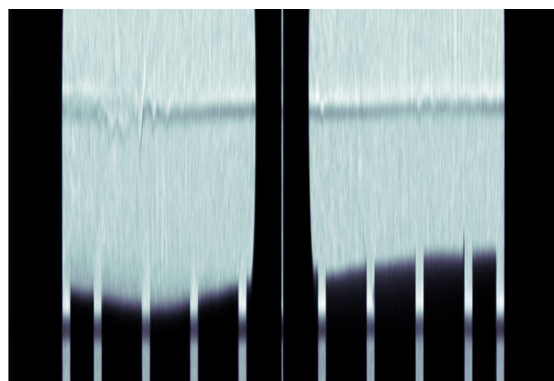
Layers by standard process that fail specifications

C130521-AB-3   K = 1.54 um, TGD = 41.5 um

Fuel layer
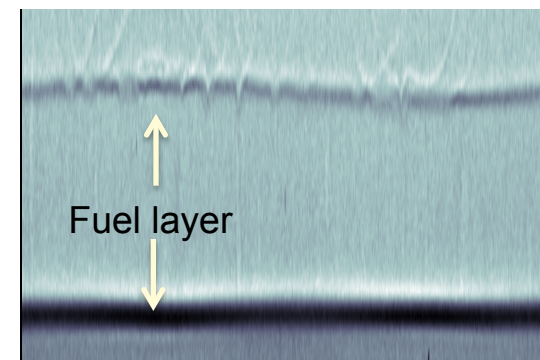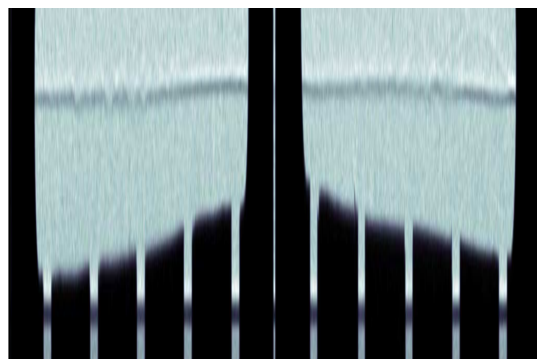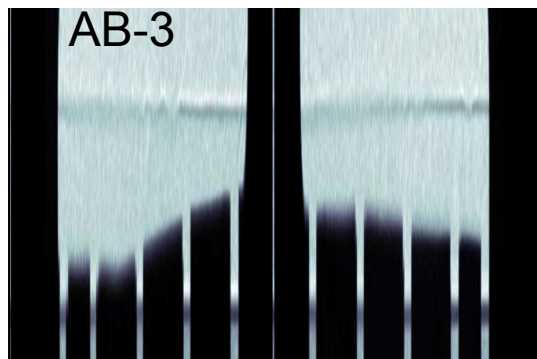
C131104-AA-1   K = 1.26 um, TGD = 23.8 um
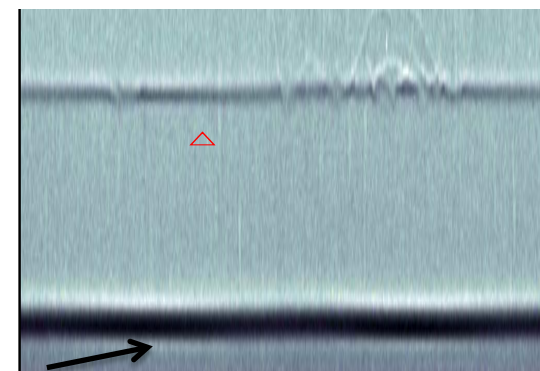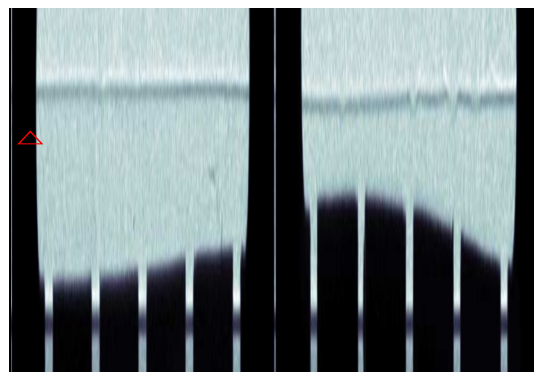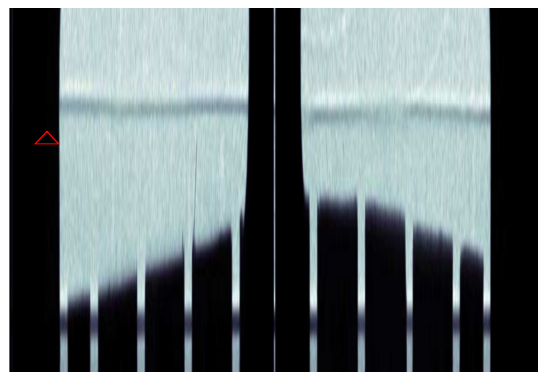
Capsule

Too many small grooves for ignition quality layers

Layers by standard process that fail specifications

C140610-AA-1 (dev) (not shimmed)

C140809-AA-1 Aborted at 10 hrs (out of 13.5 hrs)

Fuel layer
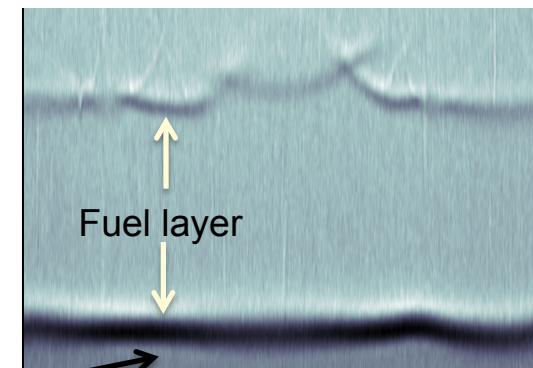
Capsule

C140610-AA-4   Aborted at 10 hrs (out of 13.5 hrs)
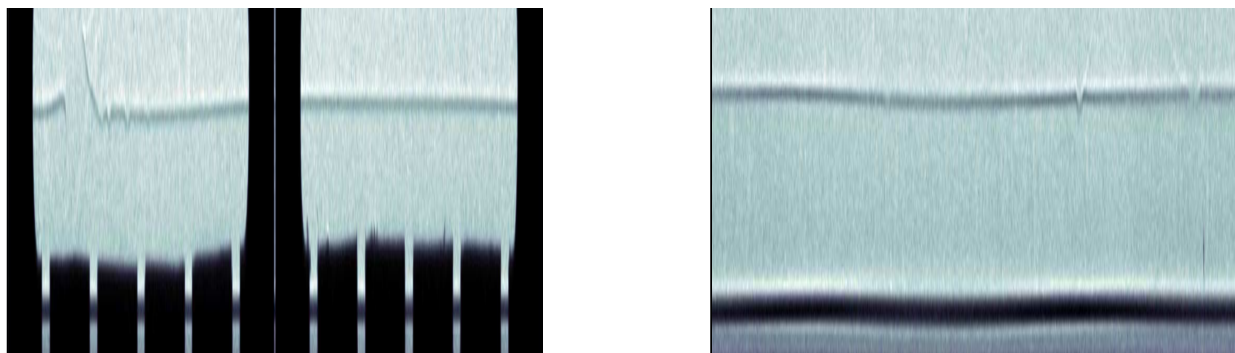
Layers by standard process that fail specifications

C131213-AB-1 (10 hrs)

Fuel layer
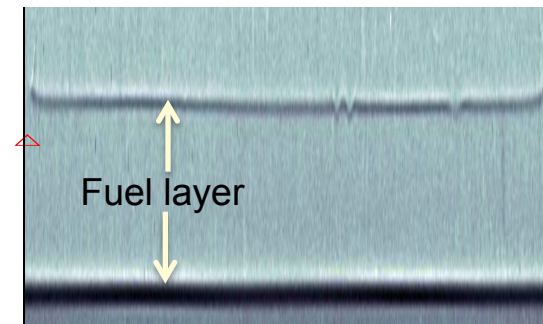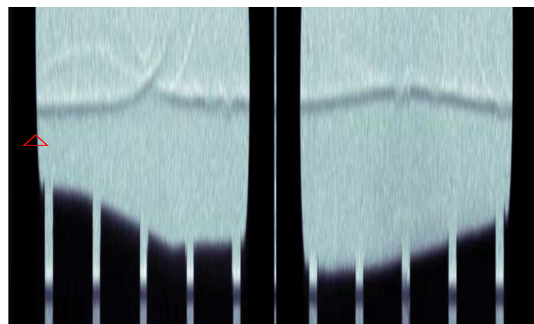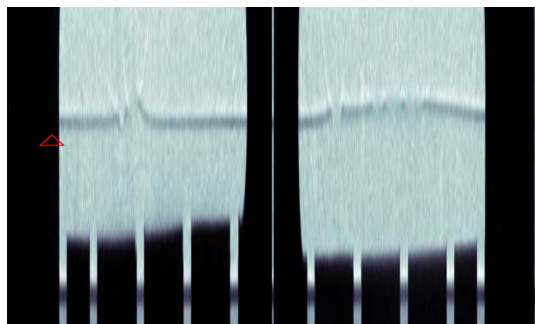
C140109-AA-3
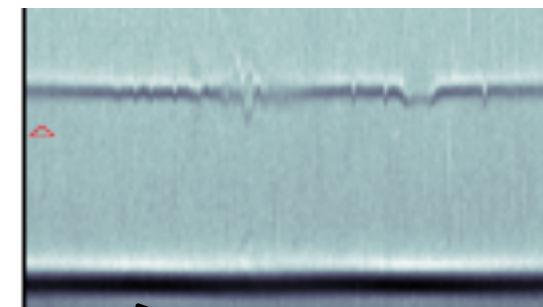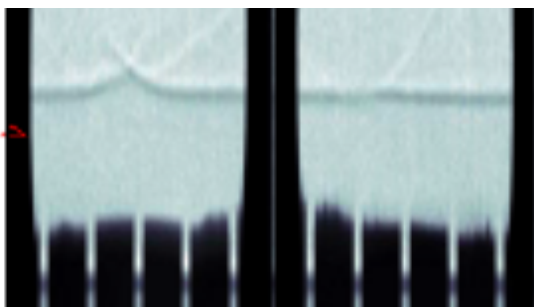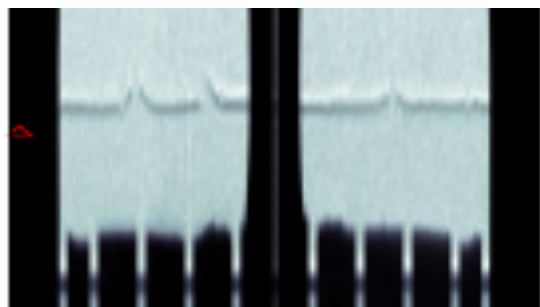
Capsule

C130427-AA-1
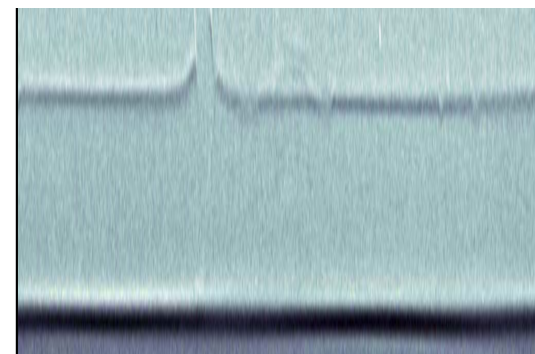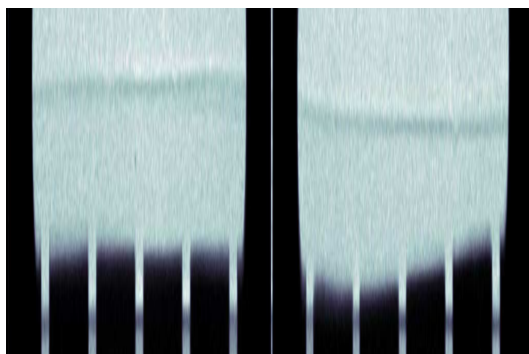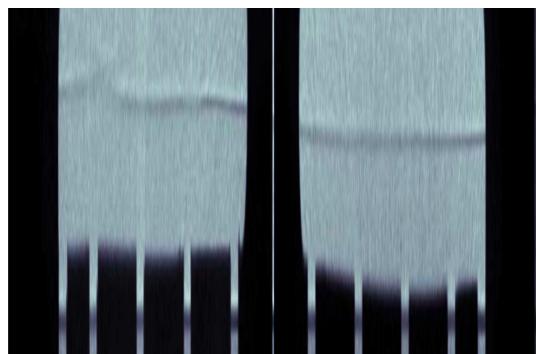
Some particularly bad LEH features in the field

LEH-4738-A16

C120804-AA-1

C130320-AA-4

C140804-AA-2

C130320-AA-2

C130320-AA-3
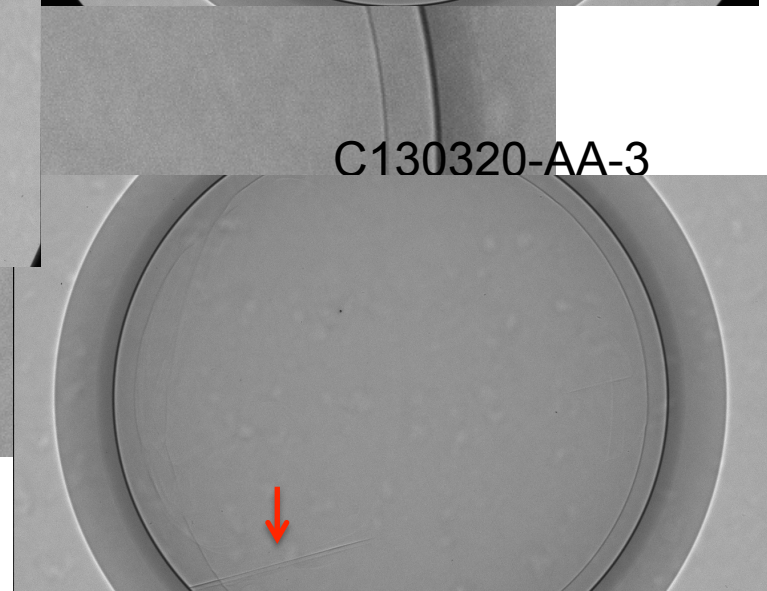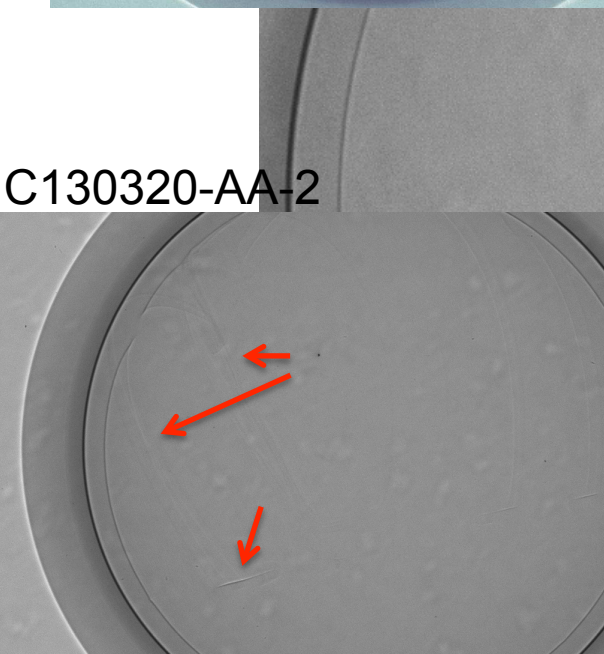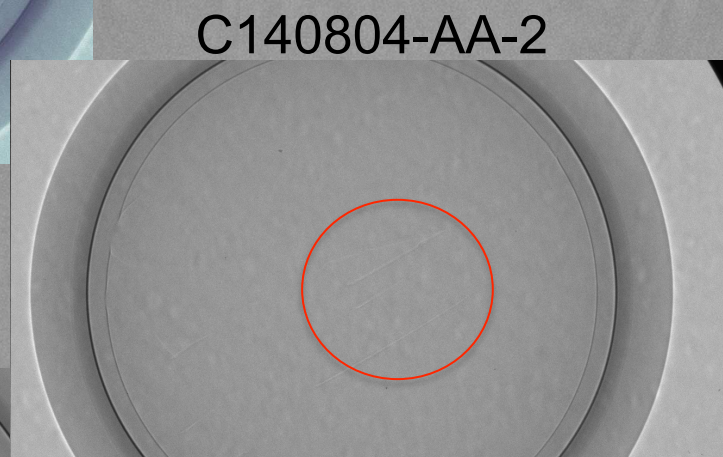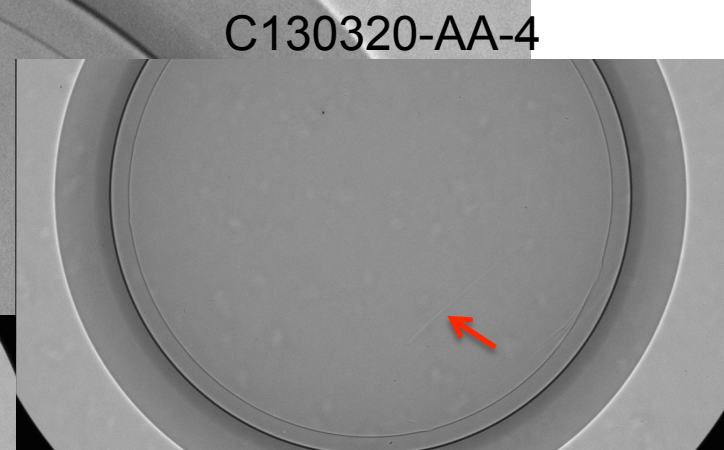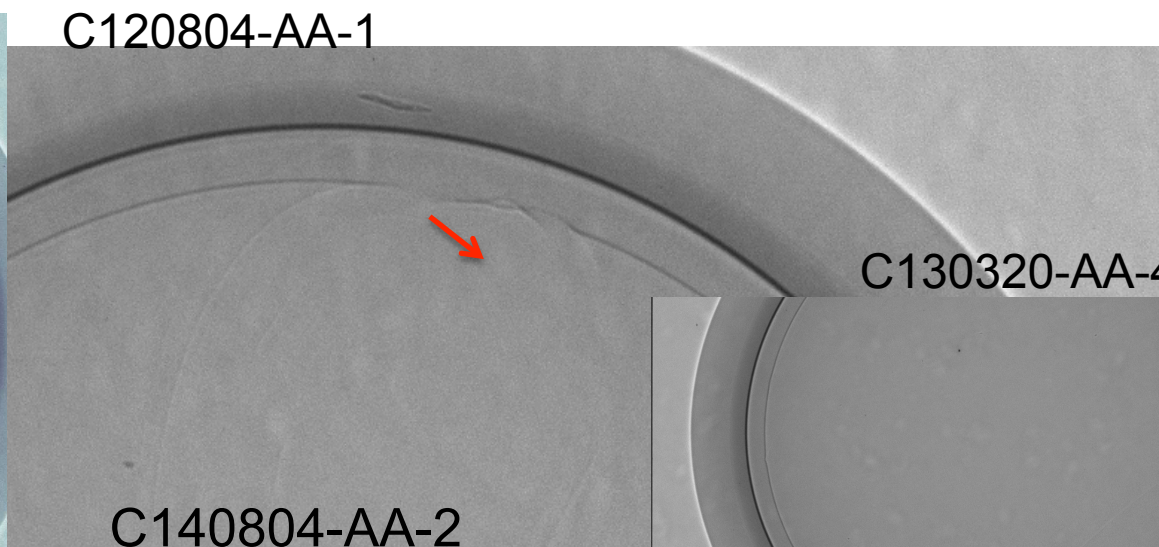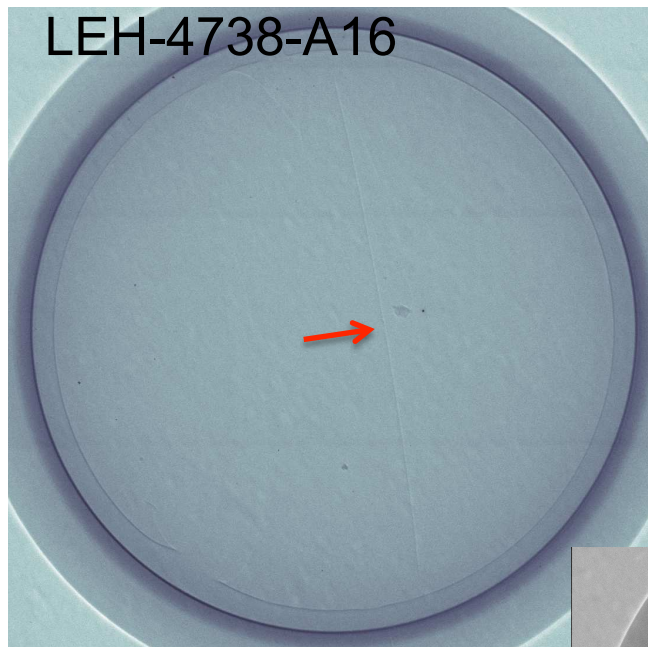
Thermal cycling works on layers with one "stuck" defect

LEH view of large defect in layer, before thermal cycle

Groove extends to inner capsule surface

Groove nearly all the way around shell

Thermal cycling works on layers with one "stuck" defect

LEH view after thermal cycle
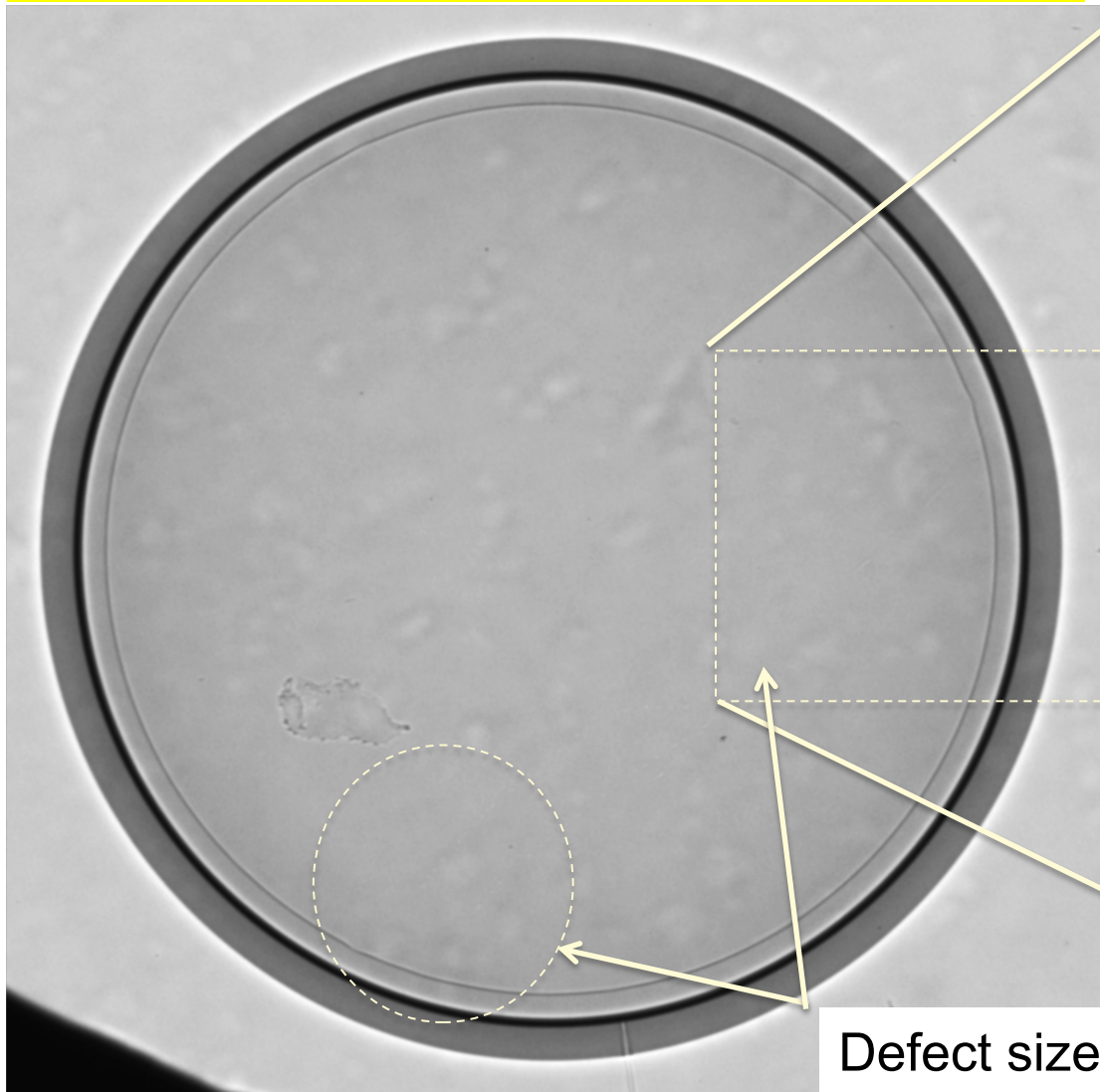
Few 'bubbles' appear along line of original defect
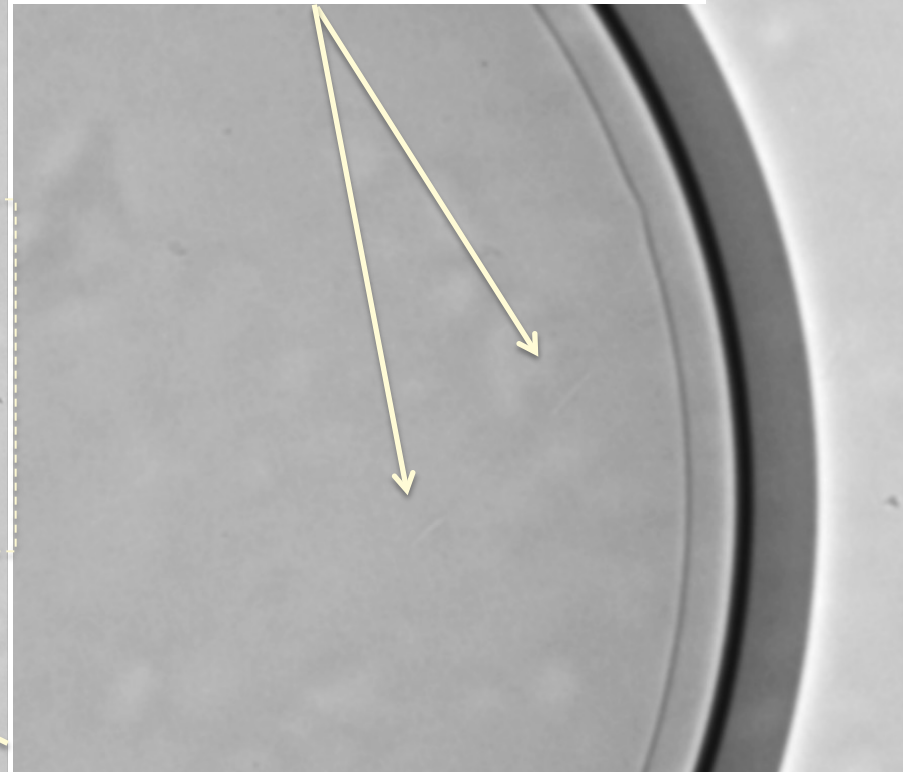
Defect size greatly reduced

Unwrapped images, before thermal cycling, defect only in the LEH view
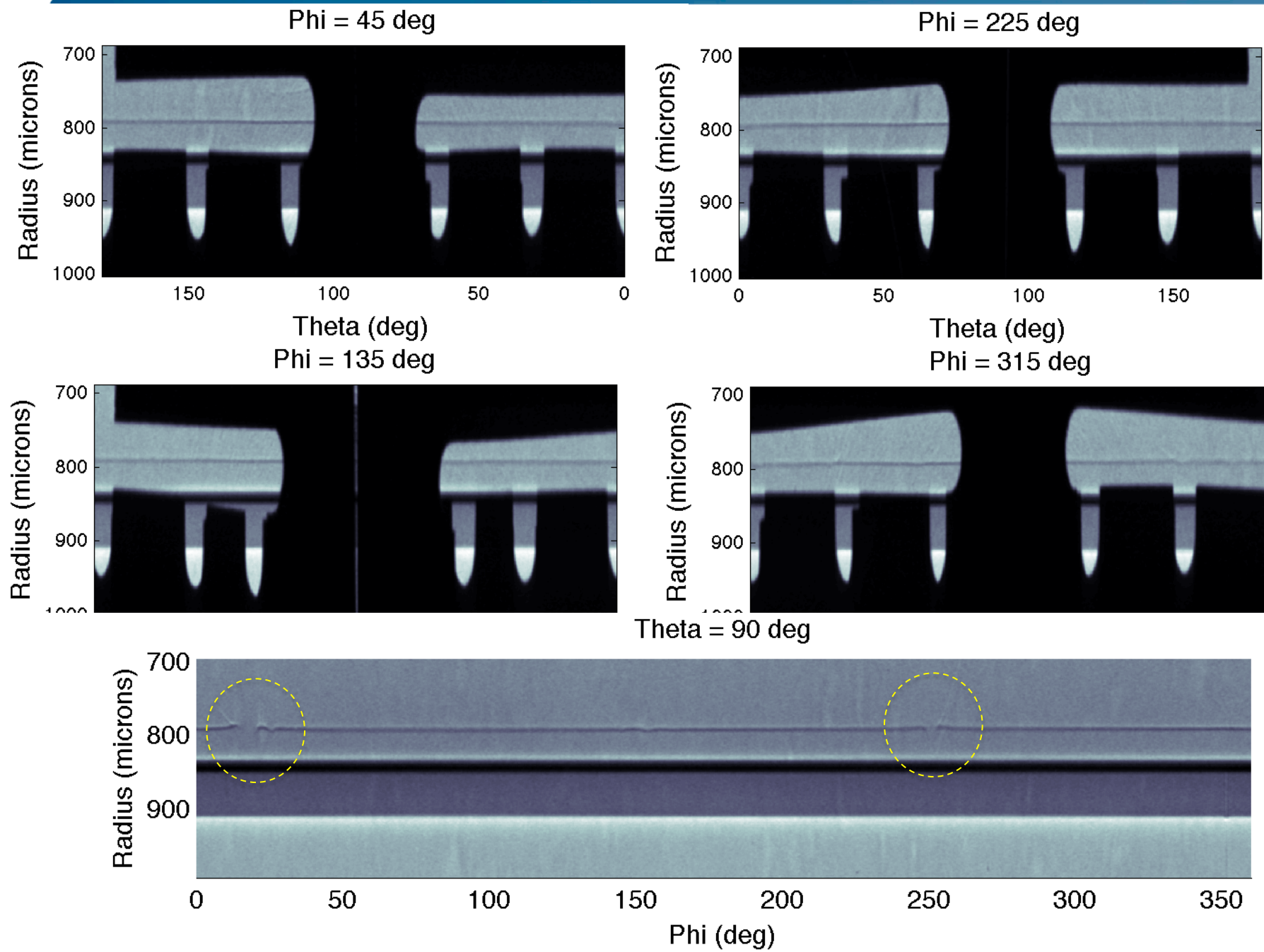
Unwrapped images, *after* thermal cycling, defect only in the LEH view
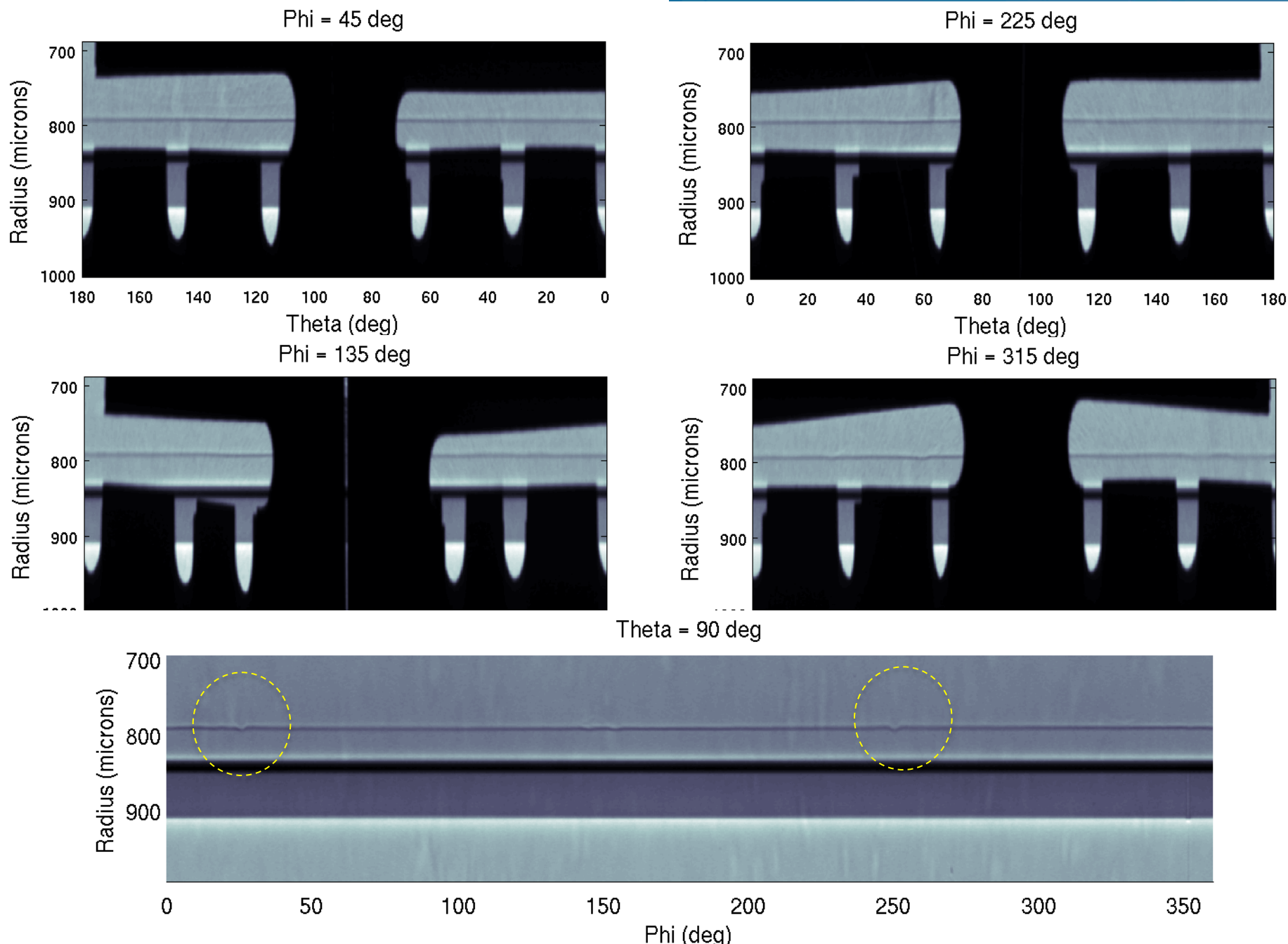
Thermal cycling notes

- Thermal cycle works best on layers with one large defect, as though crystal growth was stuck and needed a kick

- Usually one cycle is enough, not much improvement after one cycle

- Layer is partially melted during cycling. The layer needs to redistribute before getting final shape (2-3 hours). The low mode analysis will be incorrect during this 2-3 hour period.

- Thermal cycle often leaves behind bubbles, or holes in the fuel layer. Defects can still be large after thermal cycle

- Layer will be better than polycrystalline, able to measure low modes

We have not completely explored polycrystal space

- Summer student began work to characterize:
  — Polycrystal size distribution and variation from layer to layer
  — Size distribution vs quench depth, dwell time,
  — Size distribution vs anneal time/temperature, cycling
  — Still a work in progress
- Additional areas to study
  — Should we start from liquid, or a polycrystal seed
  — Low mode measurement error vs real low mode power
- We can test low-mode measurement error in ITPS
  — Much of summer was spent testing wetted foam, didn't get to test low-mode measurement of polycrystal vs good layer

Polycrystalline layers formed by liquid quench

Liquid 19.8 K
Time = 0
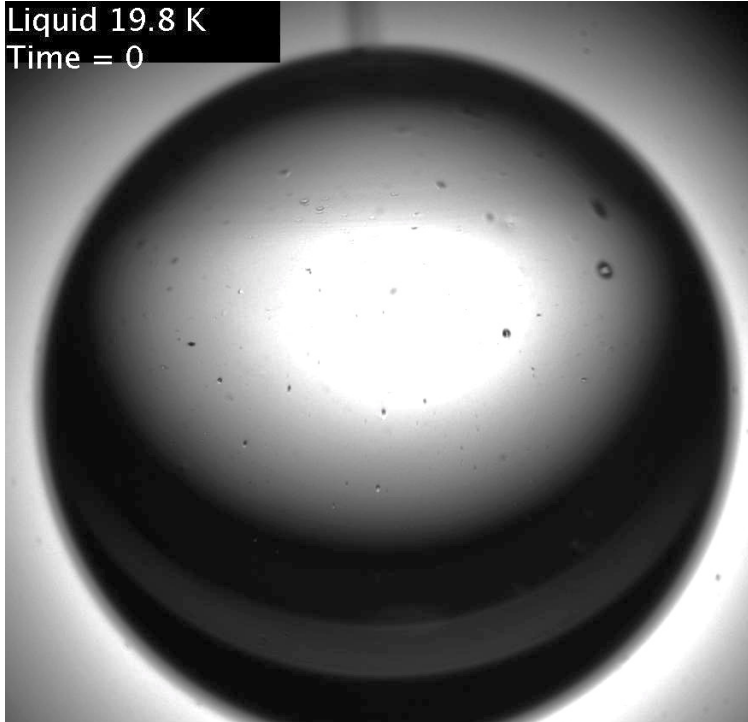
Solidifying 18.8 K
Time = +30s
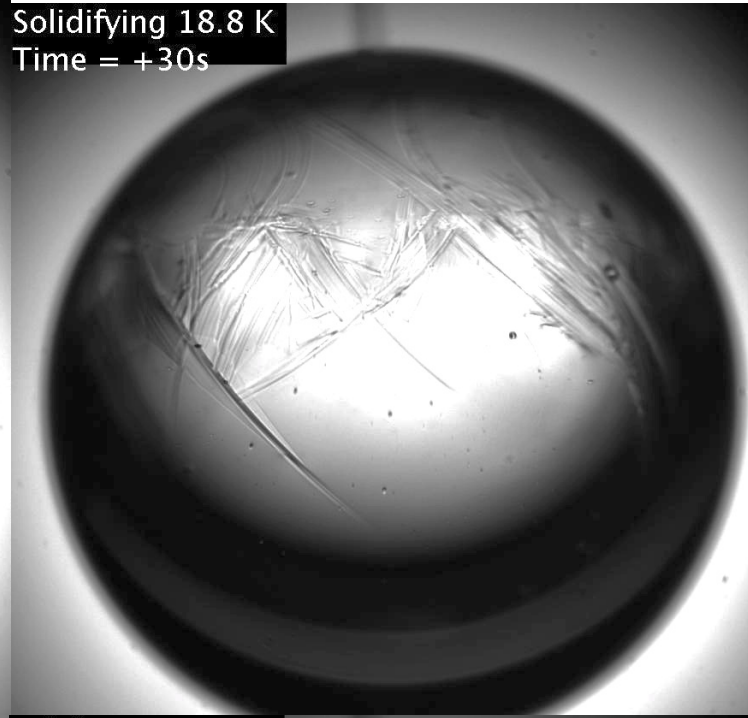
Solid 18.8 K
Time = +60s
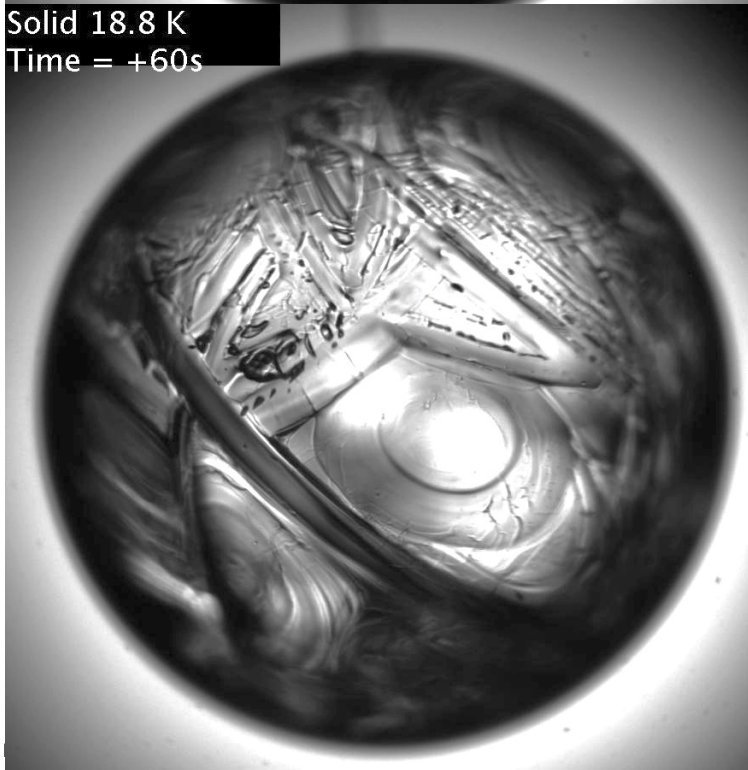
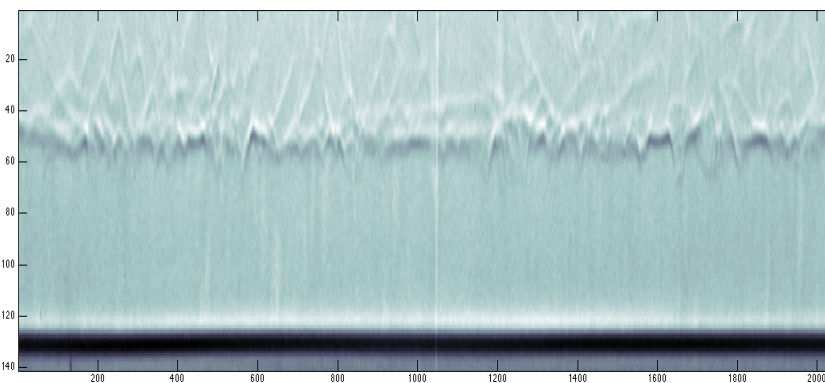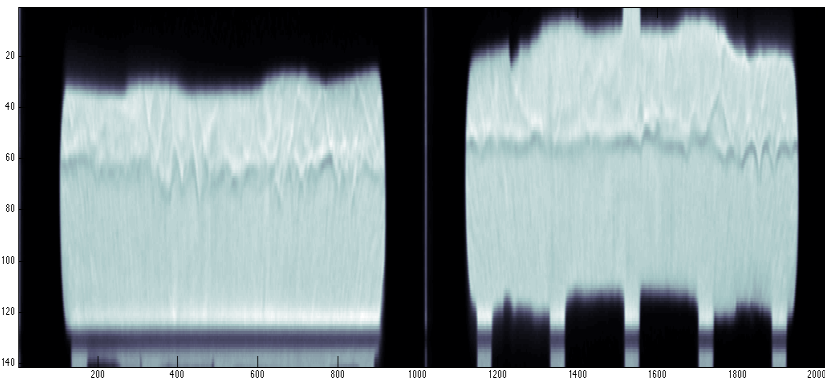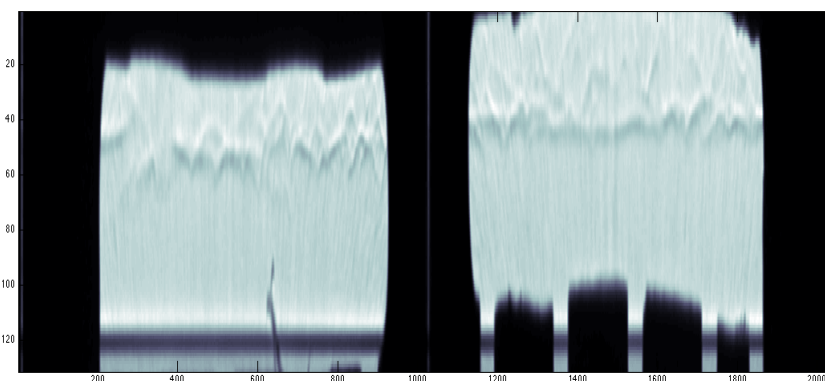Solid 18.8 K
Time = +3.5 h
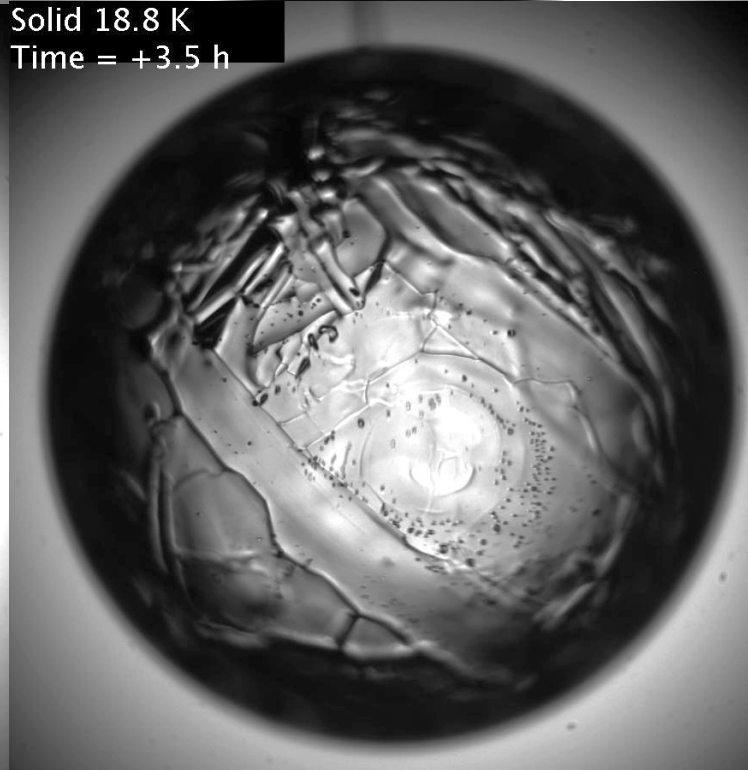
Optical images, 40 µm CH shell

Polycrystalline layers are difficult to characterize by our standard methods – Edges are often double valued
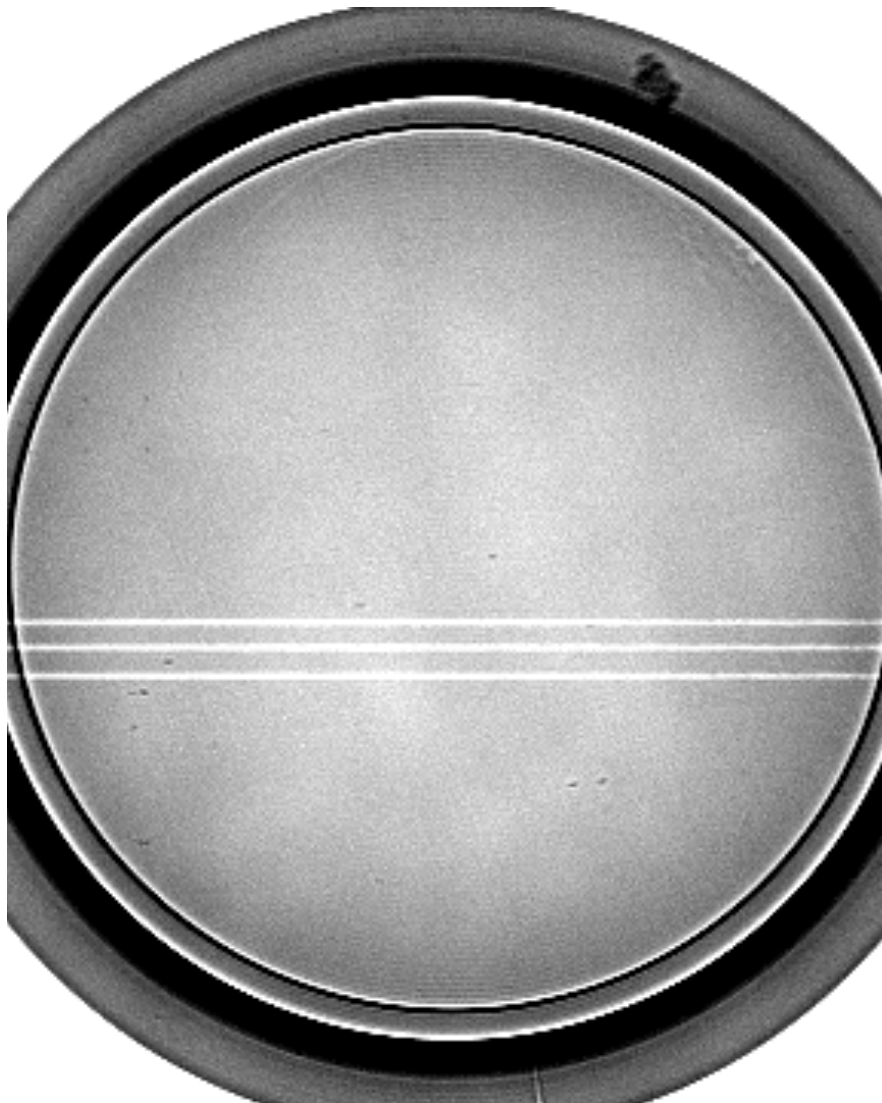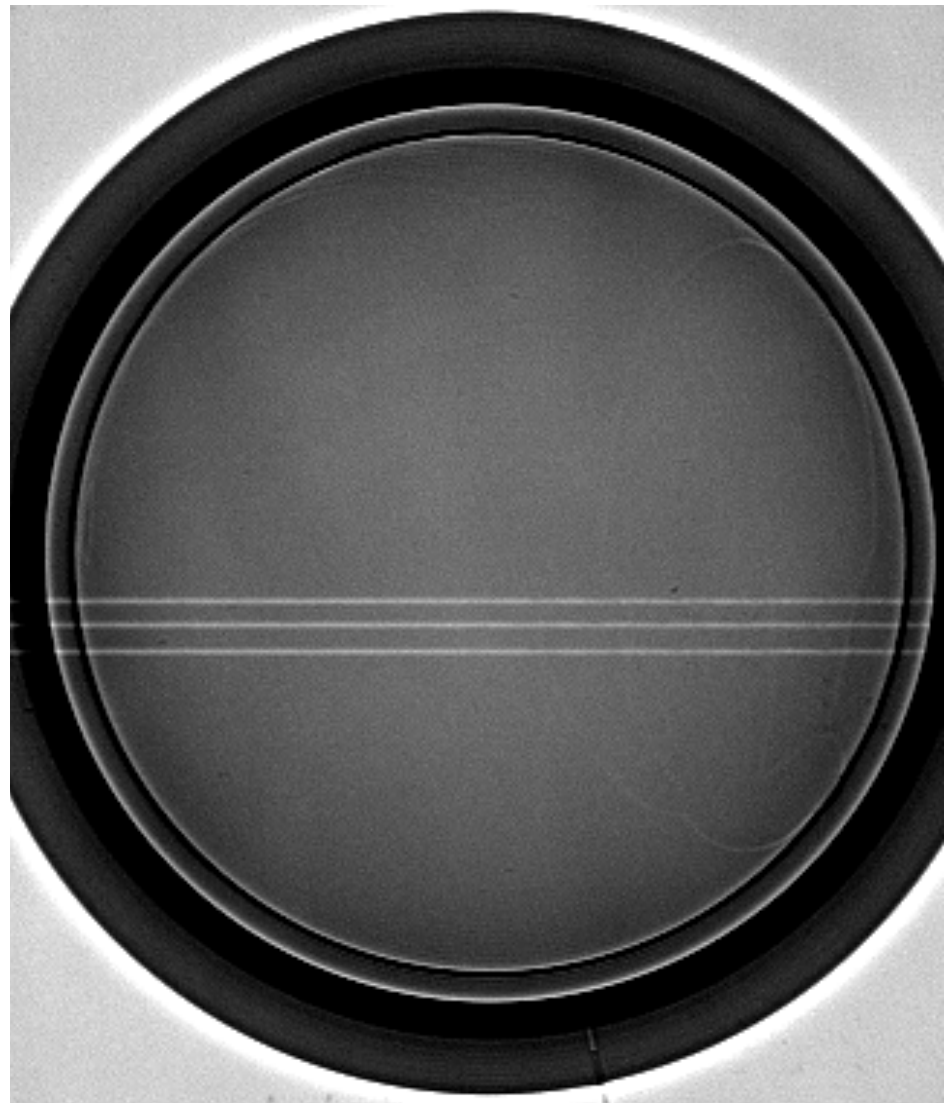
C150212-AA-PC
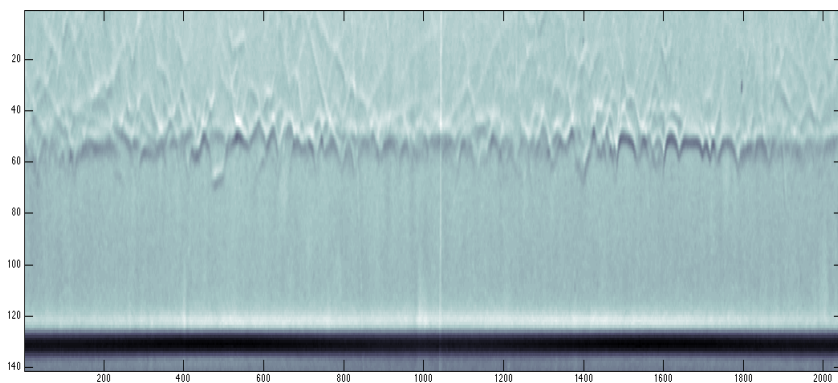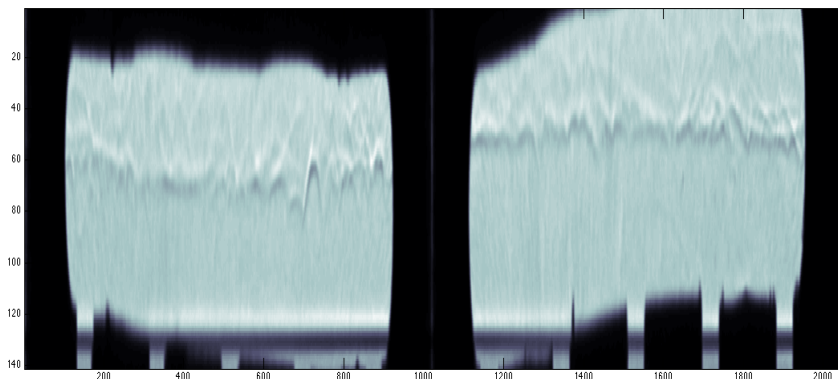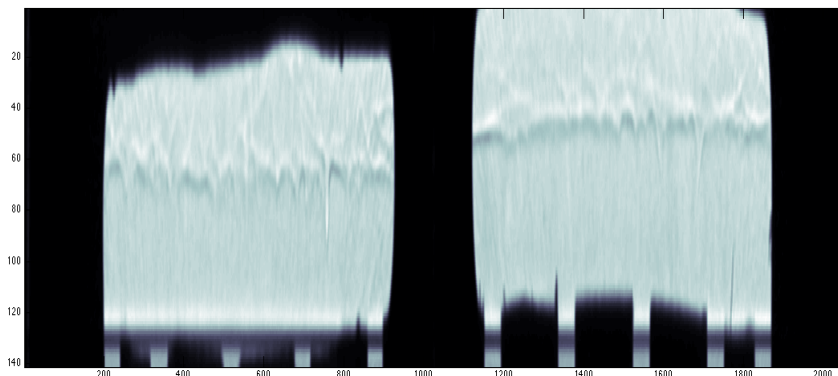
C150116-AA-PC

Stacks of 900 low mag images on single crystal layers show a handful of relatively shallow grooves
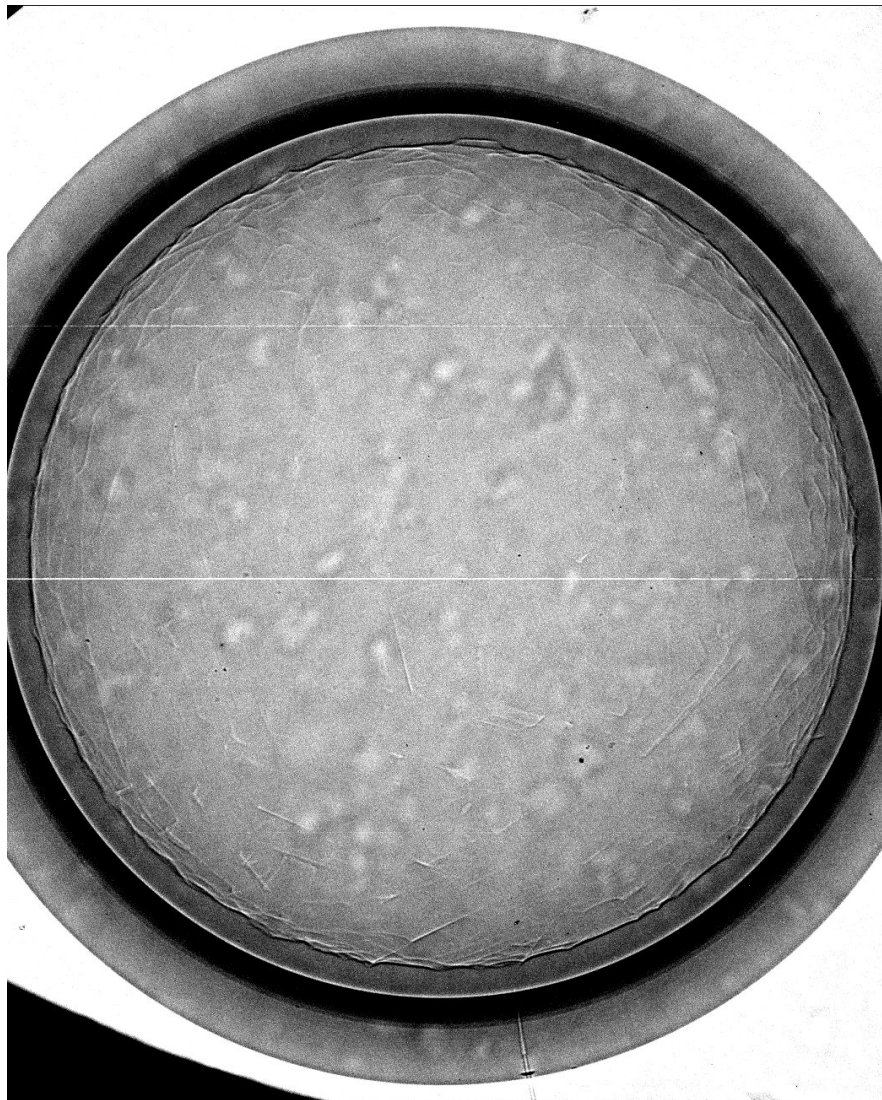
C150212-AA

C150116-AA

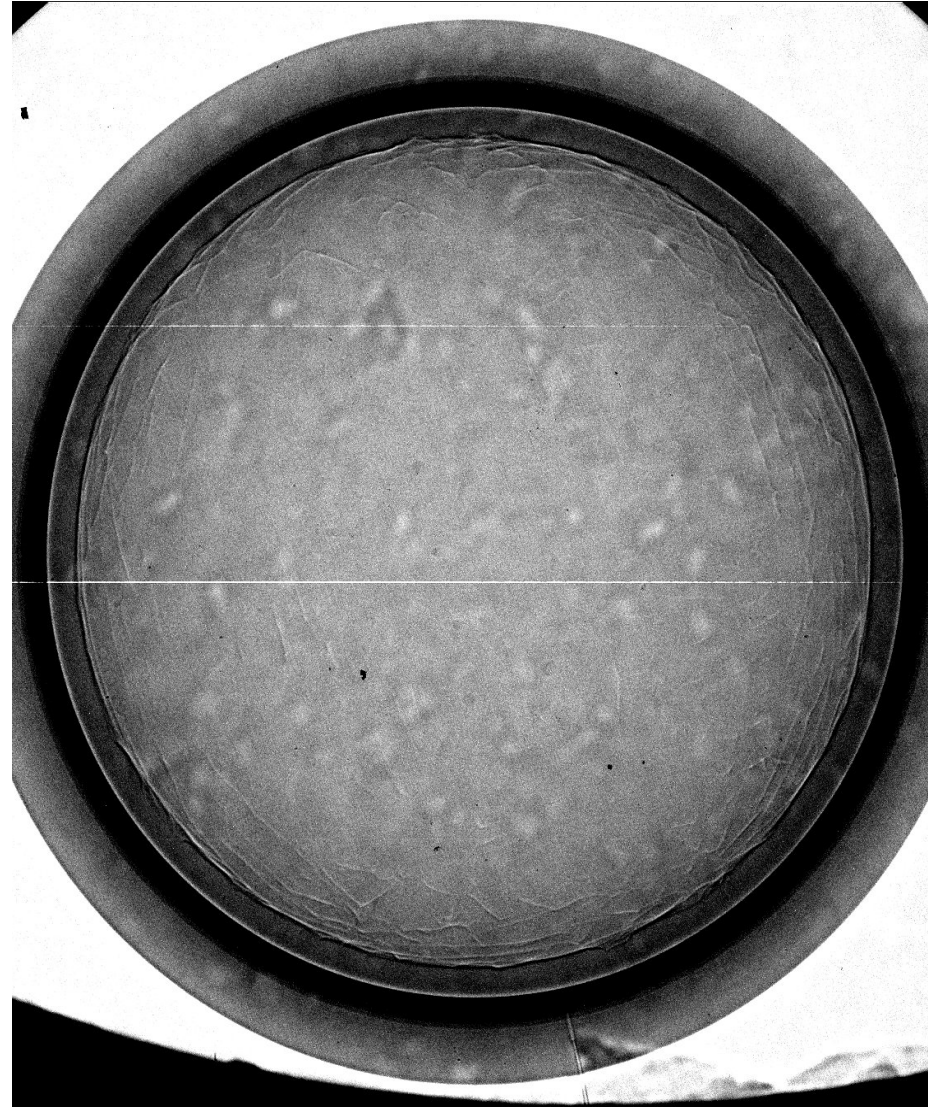# In contrast, stacks of 32 polycrystalline images reveal a large number of deep grooves

C150212-AA-PC

C150116-AA-PC

The fastest we could turn around a poly crystalline layer with the current process is ~8 hrs from fueling.

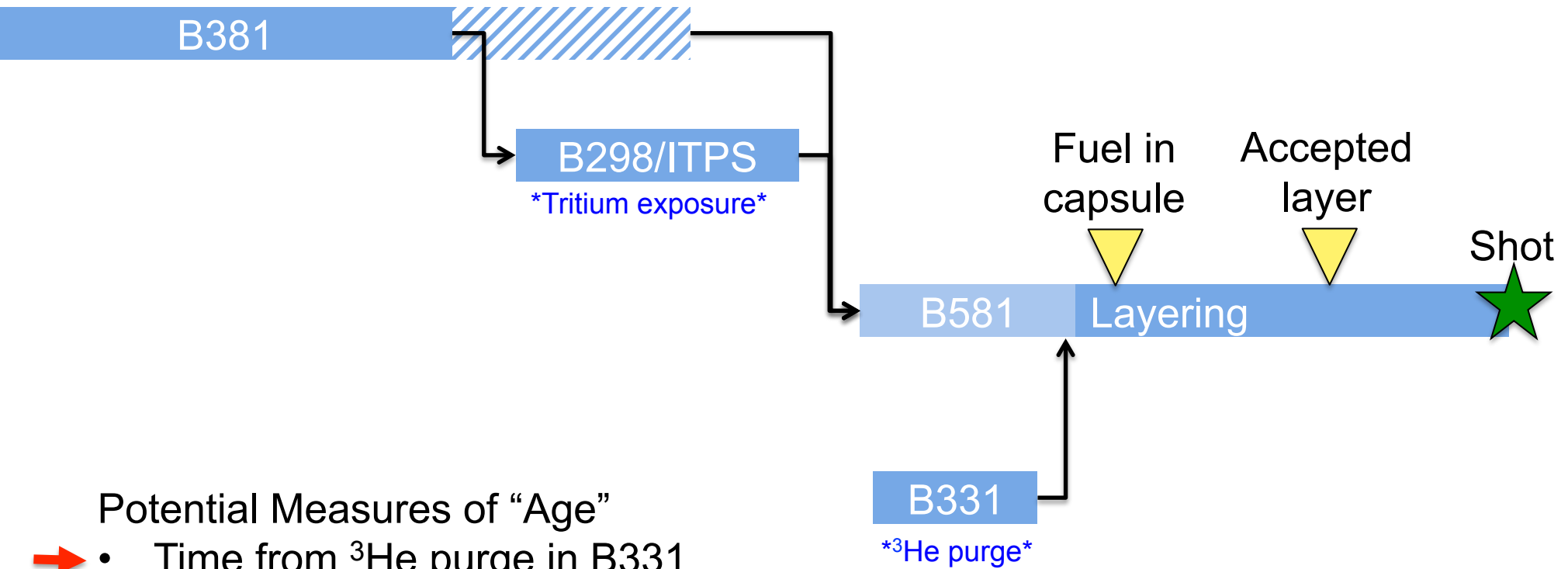1 hr – inventory set
3 hrs – beta layering
4 hrs – shimming

Single attempt (+ 1.5 hrs for each additional attempt)
No low mag characterization (+ 4 hrs)
Shimming would be within +/- 0.5 μm (better number TBD)

Better shimming confidence 0.25 μm (better number TBD) could be achieved by shimming using a single crystalline layer of TQ or better (+ 24 hrs)

(Recall: ITPS shimming parameters do not directly translate.)

# There are several tritium-related "clocks" that could be considered.

B381

B298/ITPS
Tritium exposure

Fuel in capsule

Accepted layer

Shot

B581 Layering

B331
³He purge

Potential Measures of "Age"
- Time from ^{3}He purge in B331
- Time from capsule inventory set
- Time from layer freeze
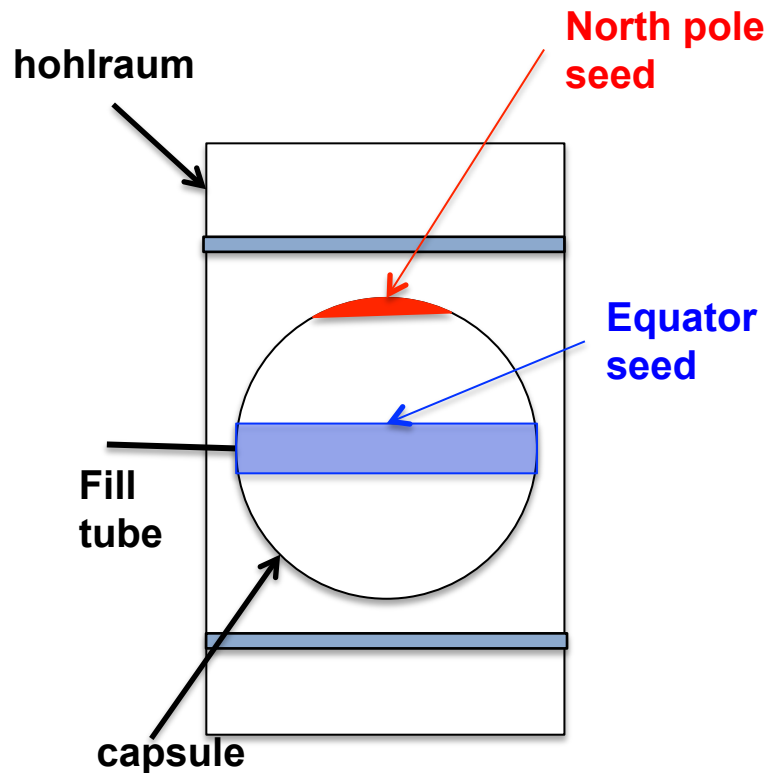- Total T soak-time in capsule

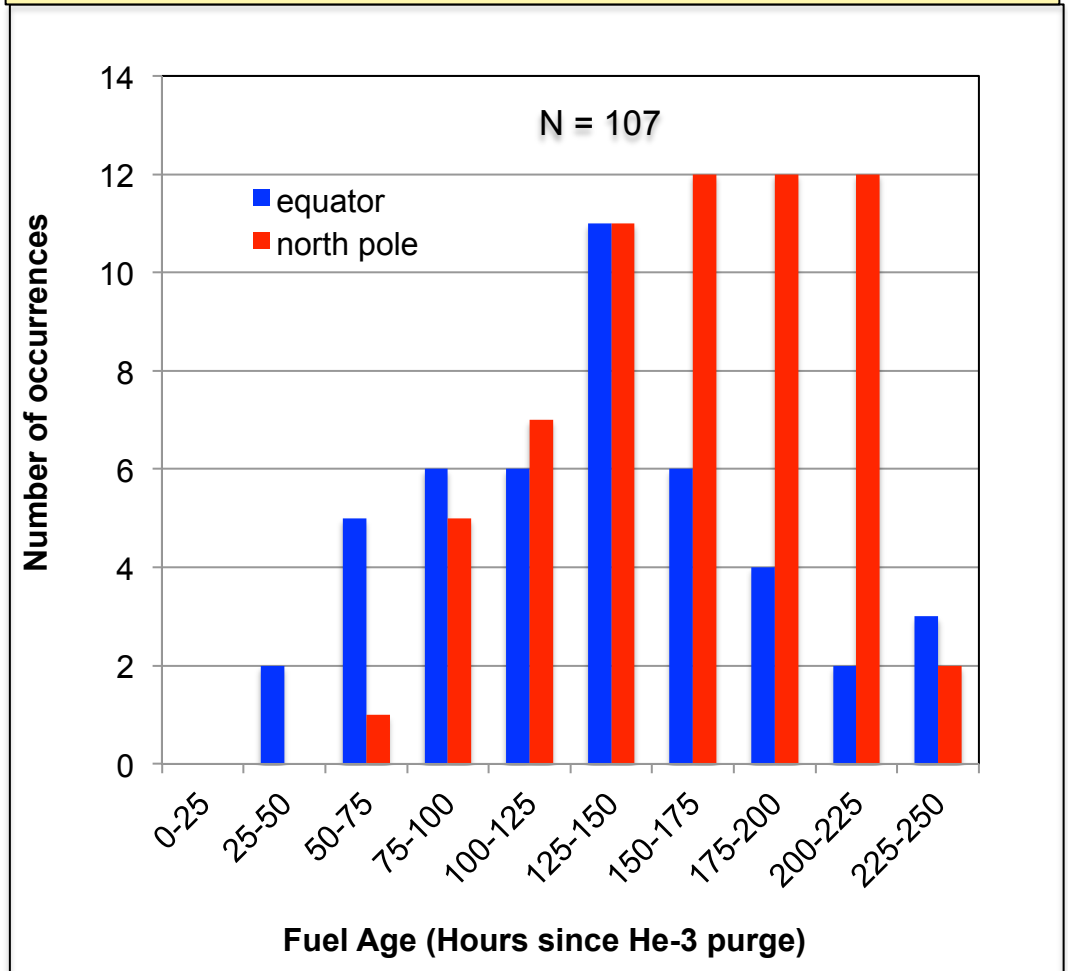# The quality of layers does not decrease as fuel ages, but the number of lost seeds does.
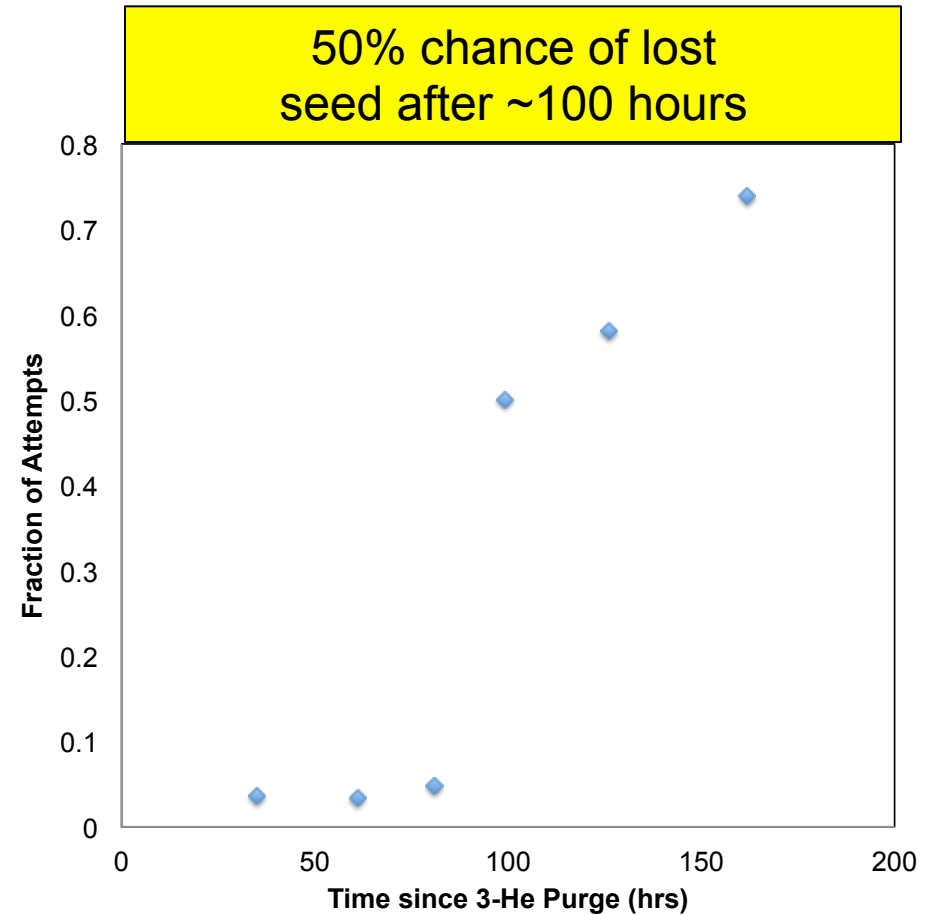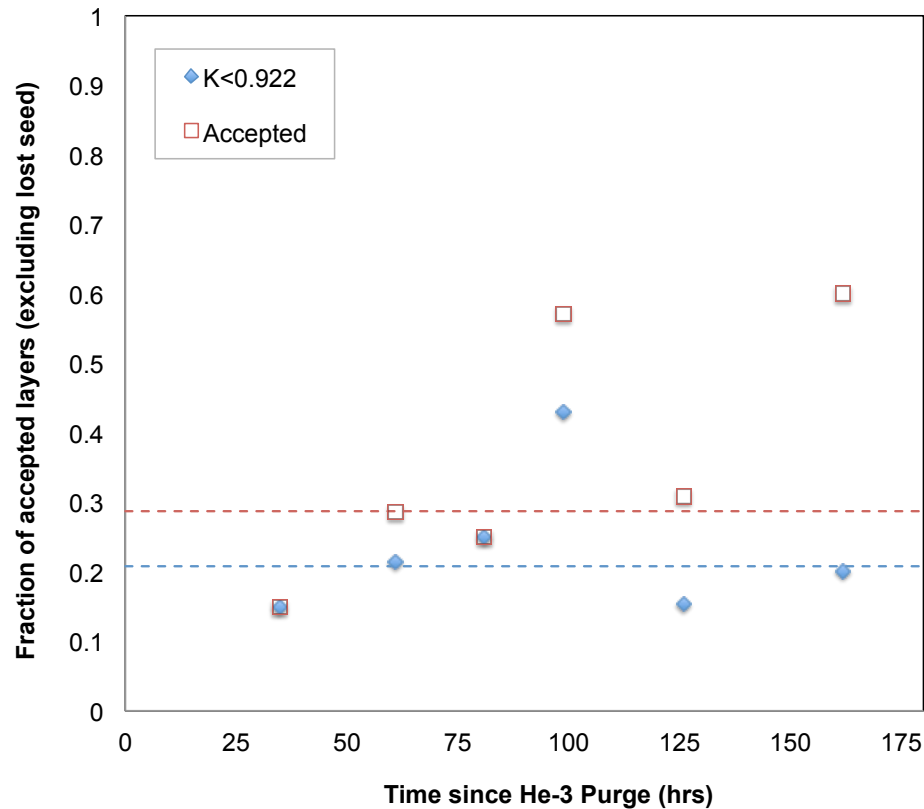
We request younger fuel because we do not want to lose seeds

Lost seeds are tied to a change in late melt location and an increase in observed melt rate
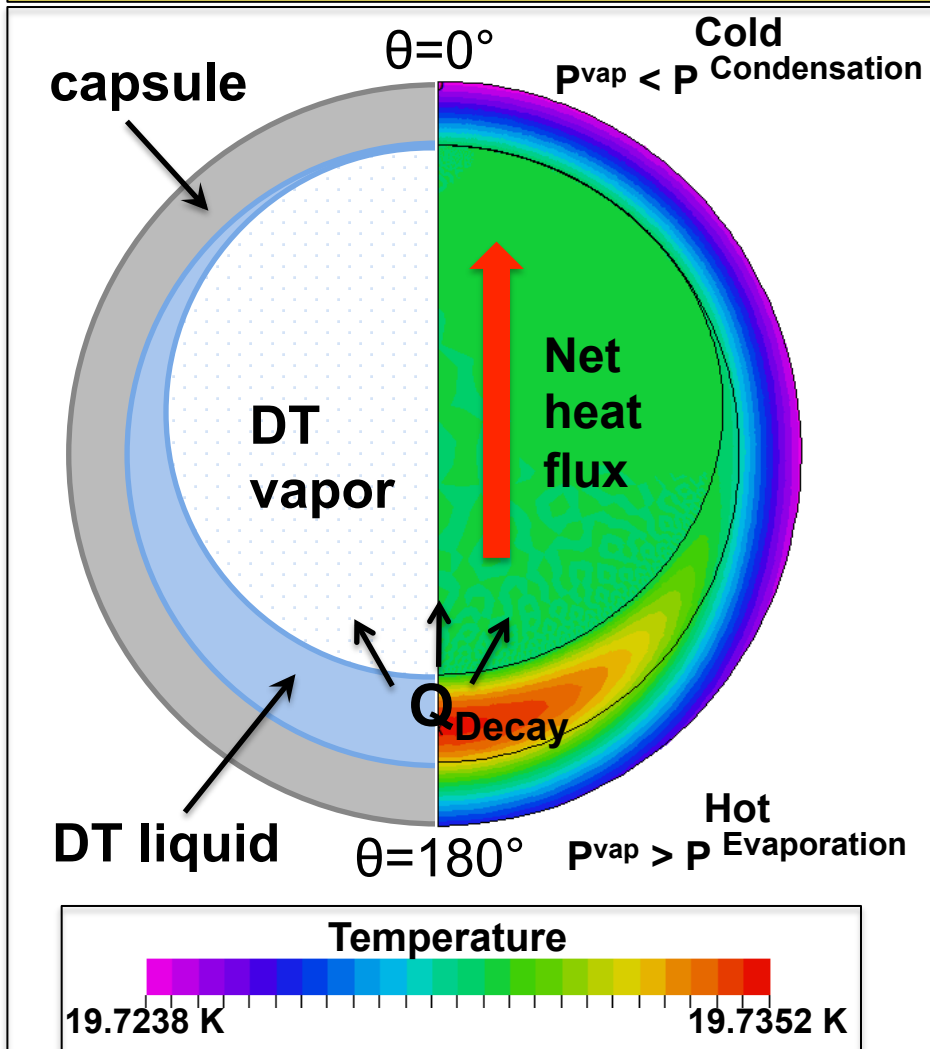
2D finite element thermal model that includes evaporation shows equator is the coldest location

Thermal model with mass transport

θ=0°

Cold
$P^{vap} < P^{Condensation}$

capsule

DT vapor

Net heat flux

DT liquid

Q_{Decay}

θ=180°

Hot
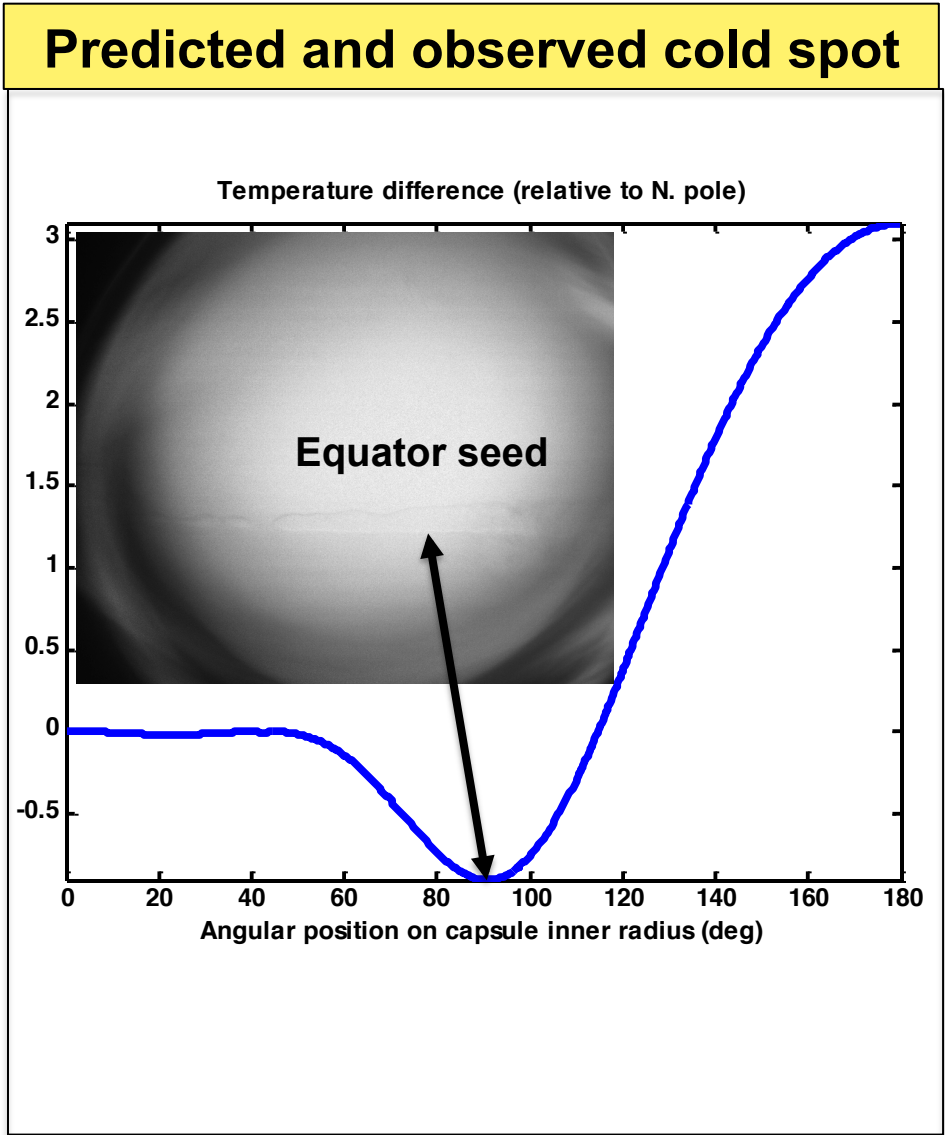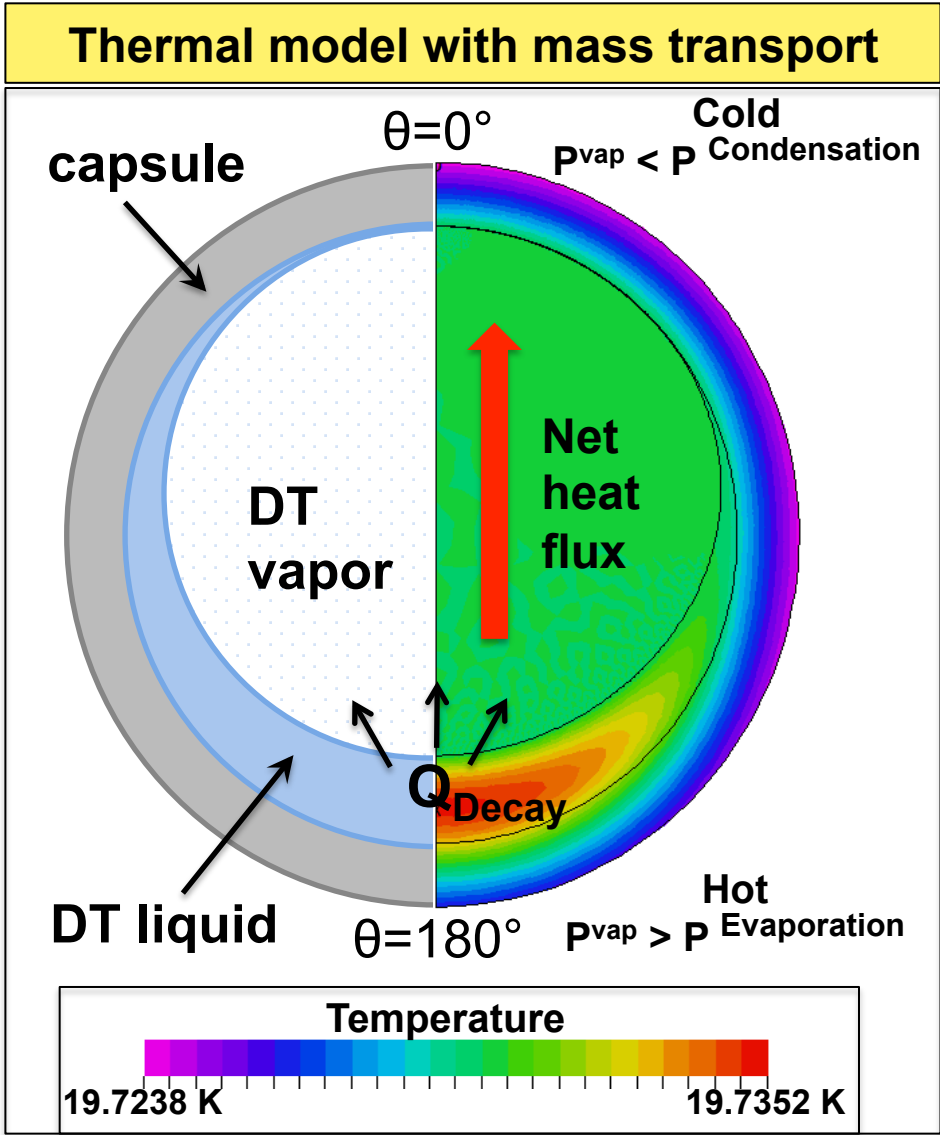$P^{vap} > P^{Evaporation}$

Temperature

19.7238 K — 19.7352 K

Assumptions:

- Tritium beta-decay is a heat source in the liquid

- Constant pressure in gas phase requires liquid—vapor surface to be isothermal

- Evaporation carries heat from bottom of the shell to top
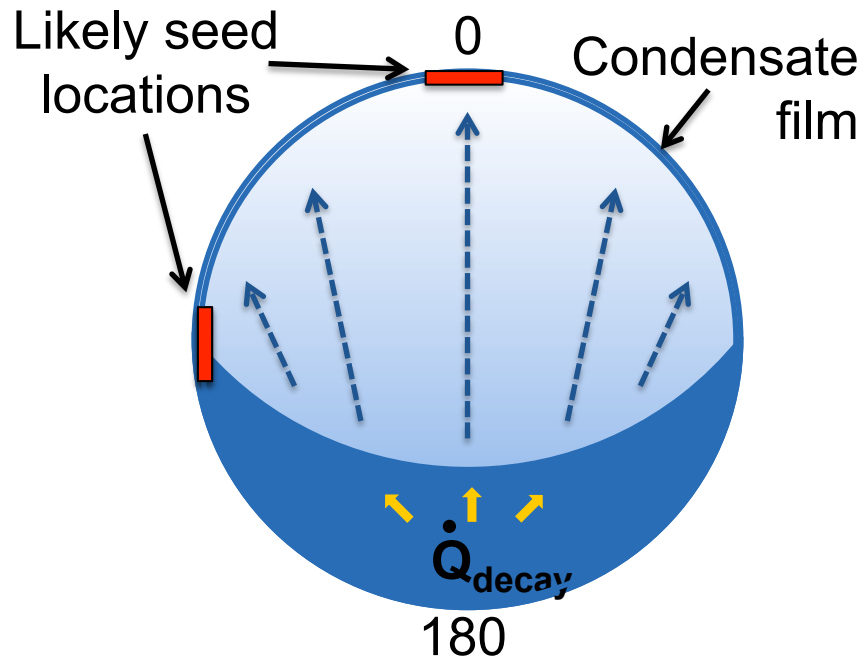
- Energy flux is product of mass flux and Δh_{vap}

2D finite element thermal model that includes evaporation shows equator is the coldest location

Thermal model with mass transport

capsule

$\theta = 0°$

Cold

$P^{vap} < P$ Condensation

DT vapor

Net heat flux

Q_{Decay}

DT liquid

$\theta = 180°$

Hot

$P^{vap} > P$ Evaporation

Temperature

19.7238 K   19.7352 K

Predicted and observed cold spot

Temperature difference (relative to N. pole)

Equator seed

ΔT (mK)

Angular position on capsule inner radius (deg)
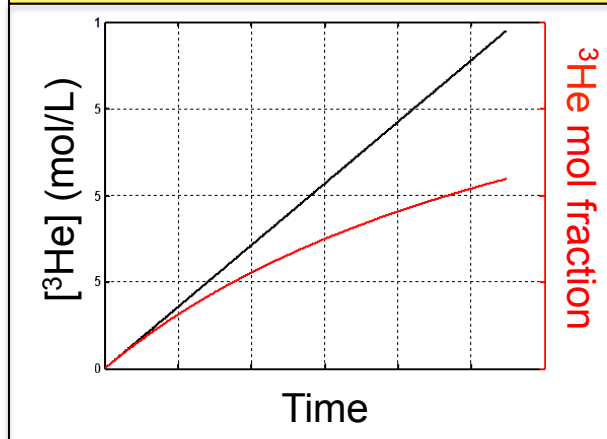
Model predicts 1-um thick condensation film and a cold spot at the capsule equator, where seeds occur at early time

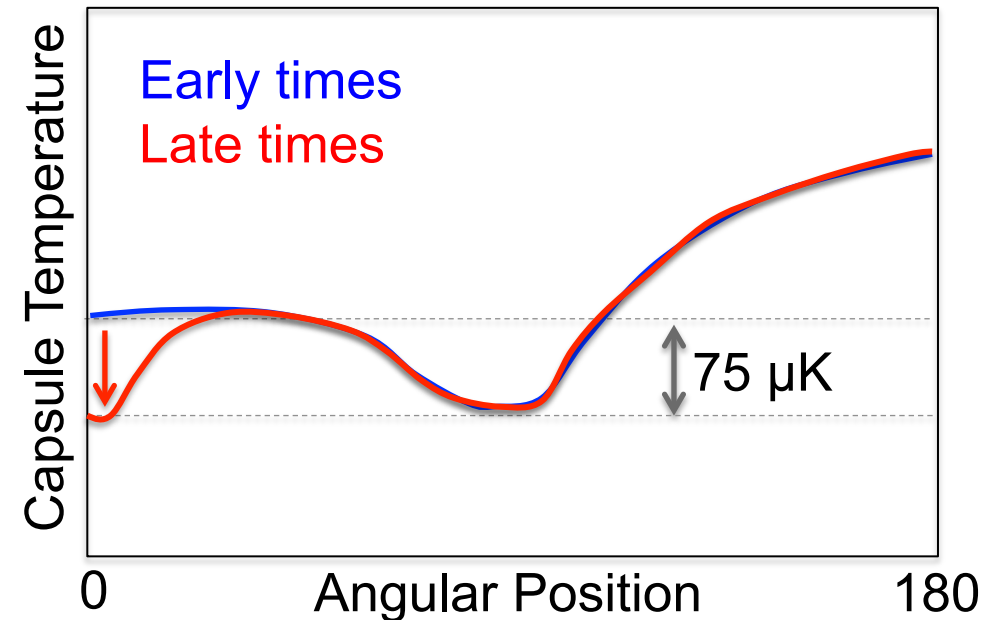# Cross diffusion through ³He is one possible cause of cold spot migration

Likely seed locations

0

Condensate film

$\dot{Q}_{decay}$

180

Time-varying capsule thermal profile

Early times
Late times

Capsule Temperature

75 µK

0   Angular Position   180

³He generated by decay

[³He] (mol/L)

³He mol fraction

Time

³He generated by decay:
- **Concentrates in vapor**
- **Impedes diffusion of hydrogens**
- **Reduces condensation**
- **Results in second cold spot**

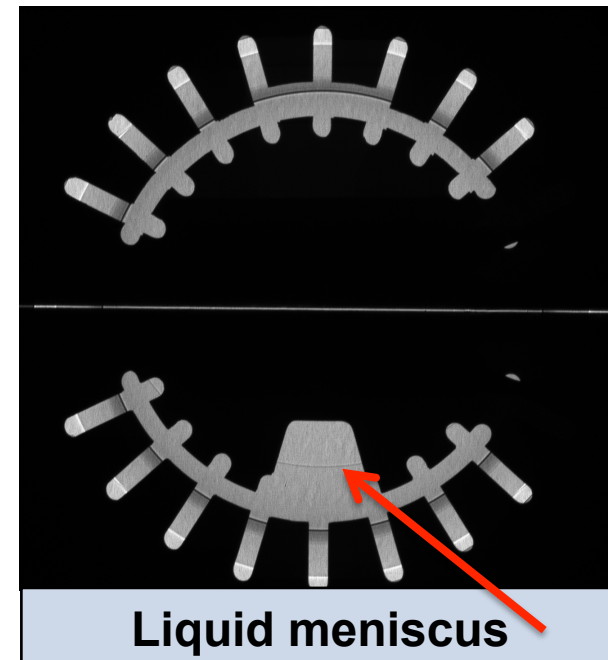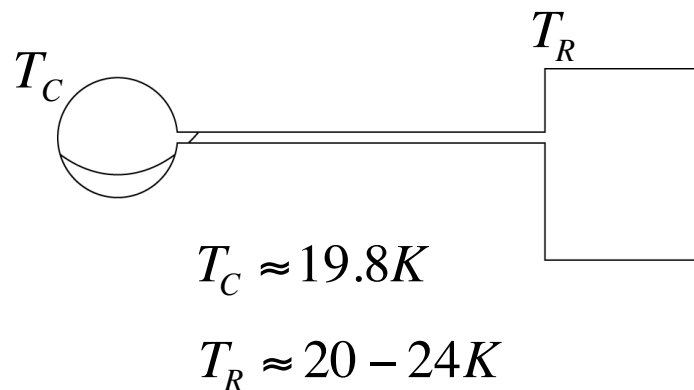**Model predicts 100-200 hrs for seed location to migrate to north pole**

NIF

- **Capsules are filled with a fill line attached to an internal reservoir in the target assembly**
- **The internal reservoir is filled from a bottle of gas delivered from LLNL's Tritium facility and attached to the target pylon.**

$$T_C$$

$$T_R$$

$$T_C \approx 19.8K$$

$$T_R \approx 20 - 24K$$
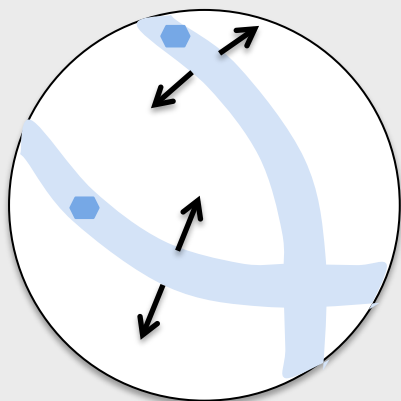
Liquid meniscus

- **Adjusting the relative temperatures of the capsule and reservoir changes the fuel volume in the capsule**

Local defects are the primary reason layers fail to meet specifications

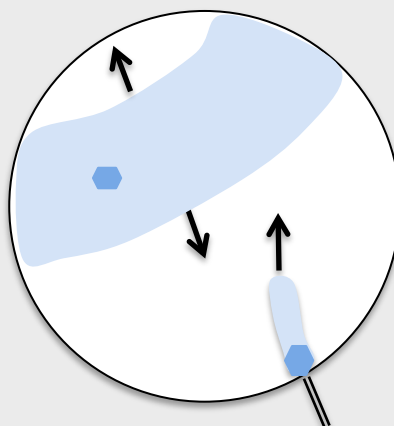## Potential mechanisms for defect formation

Multiple Seeds	Secondary Nucleation	Accumulation of Dislocations
• **Insufficient meltback (crystal #/size)** • **Poor starting material (polycrystalline layer quality, FCC phase)**	• **Seed crystal orientation & location** • **Thermal driving force**	• **Seed crystal orientation & location** • **Thermal driving force**

Electrofreezing

Templating
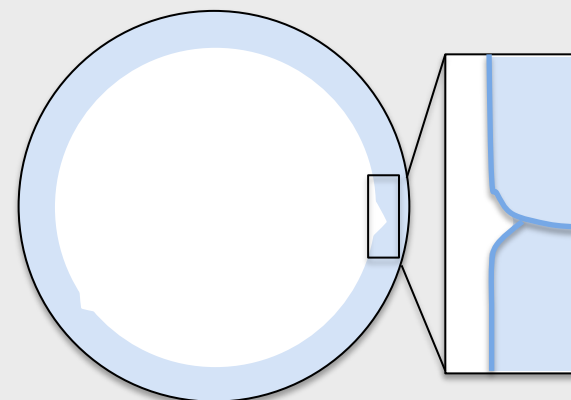
Process optimization

Process optimization

Process optimization

It currently takes around 50 hours
to produce an acceptable layer

Time Until Accepted Layer
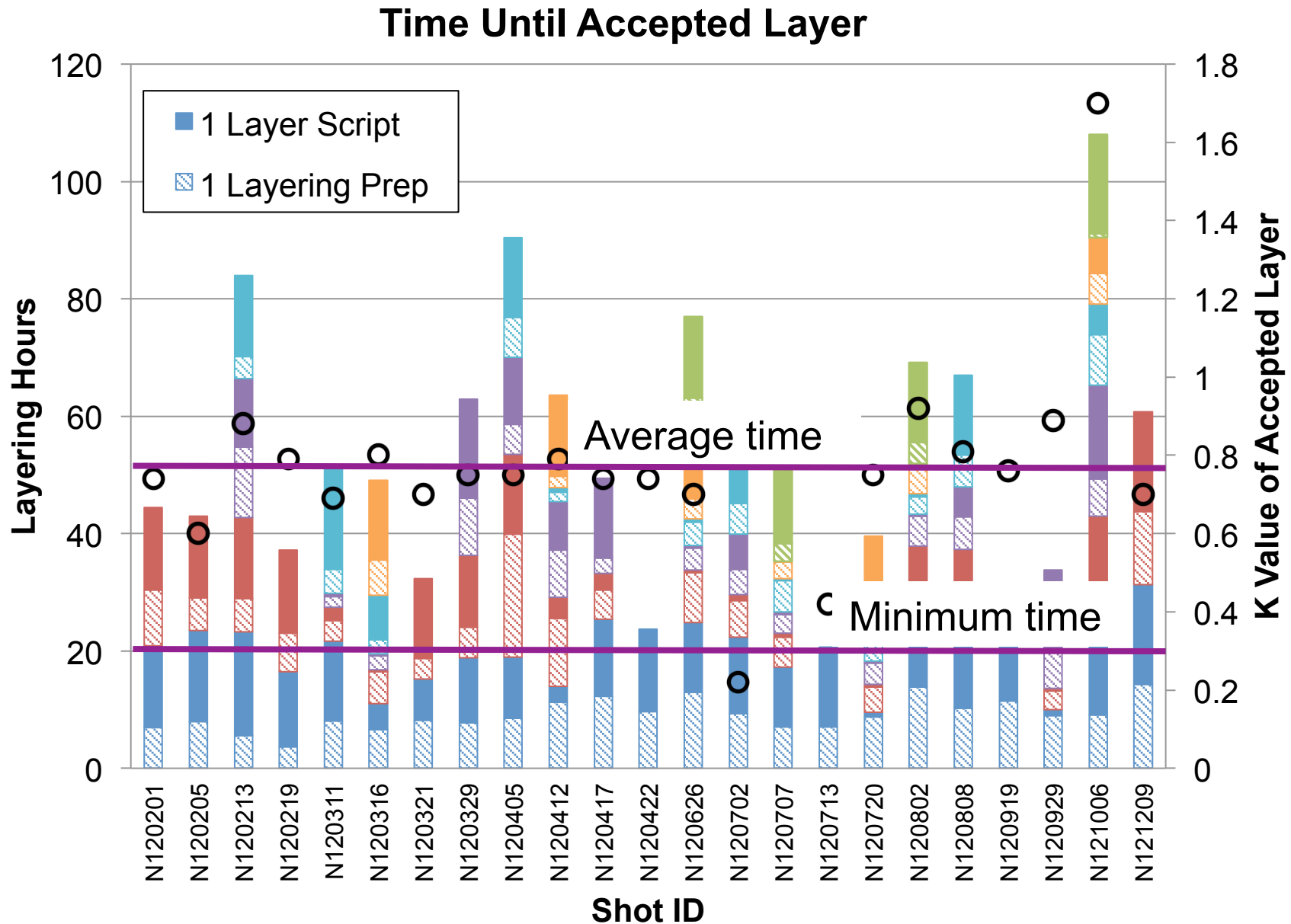
	K <= 0.922	K accepted
Lost Seed	0.32	0.32
> 1 Seed	0.19	0.19
Max Defect Area	0.24	0.24
Late Aborts (K,Low Modes, LowMag defect)	0.10	0.07
Accepted Layer	0.15	0.19

	K <= 0.922
Lost Seed	0.32
> 1 Seed	0.19
Max Defect Area	0.24
Late Aborts (K,Low Modes, LowMag defect)	0.10
Accepted Layer	0.15

|	Number of attempts			Yield, K ≤ 1.3	Yield, K ≤ 0.92
	K ≤ 0.92	0.92 < K ≤ 1.3	K > 1.3		
Excluding lost seeds	9	6	21	0.42	0.25
Only with mtol ≤ 0.008	9	3	16	0.43	0.32
Grown faster early	7	2	11	0.45	0.35
Grown faster late	2	1	5	0.38	0.25

Could we make decisions earlier based on measurement of defects?

- Standard process: Preliminary look at 10 hrs and another upon completion

- Defect analysis performed on 41 completed layers hourly for t > 5 hrs into the growth process

  - Analysis ignored obvious pole closure features

- Data was compared to final outcomes to determine when reliable predictions could be made
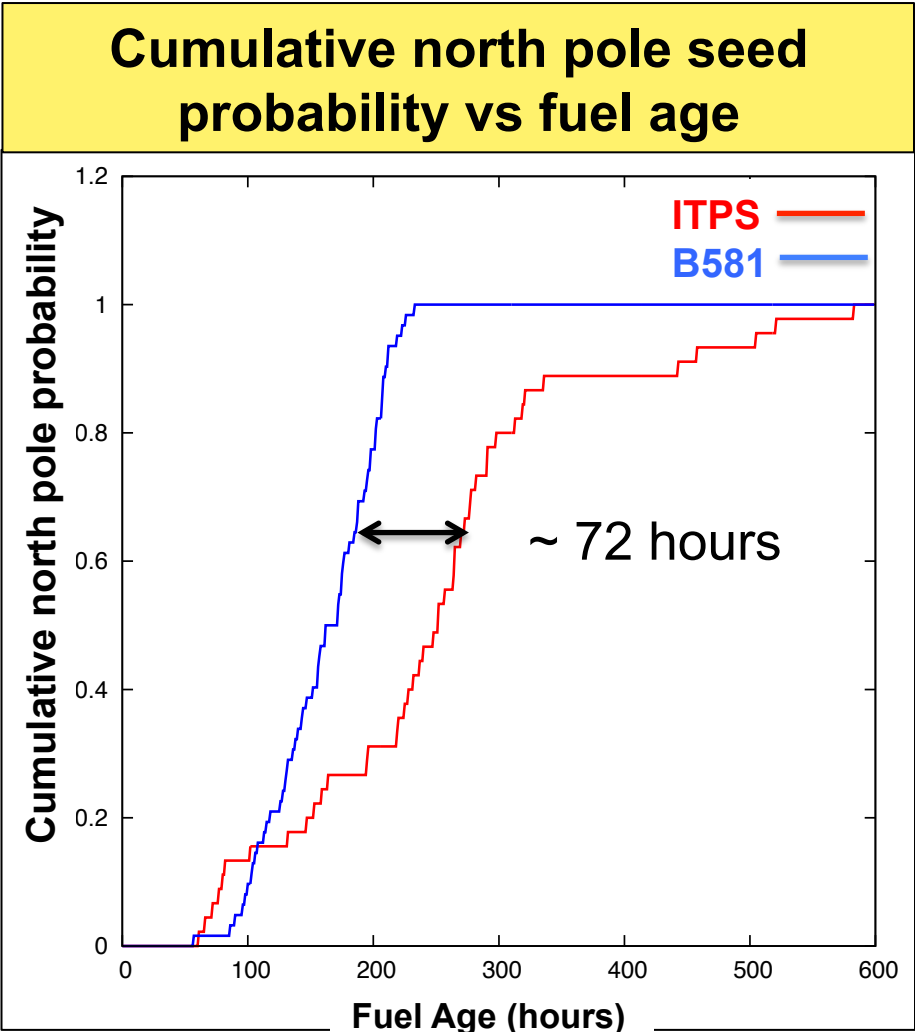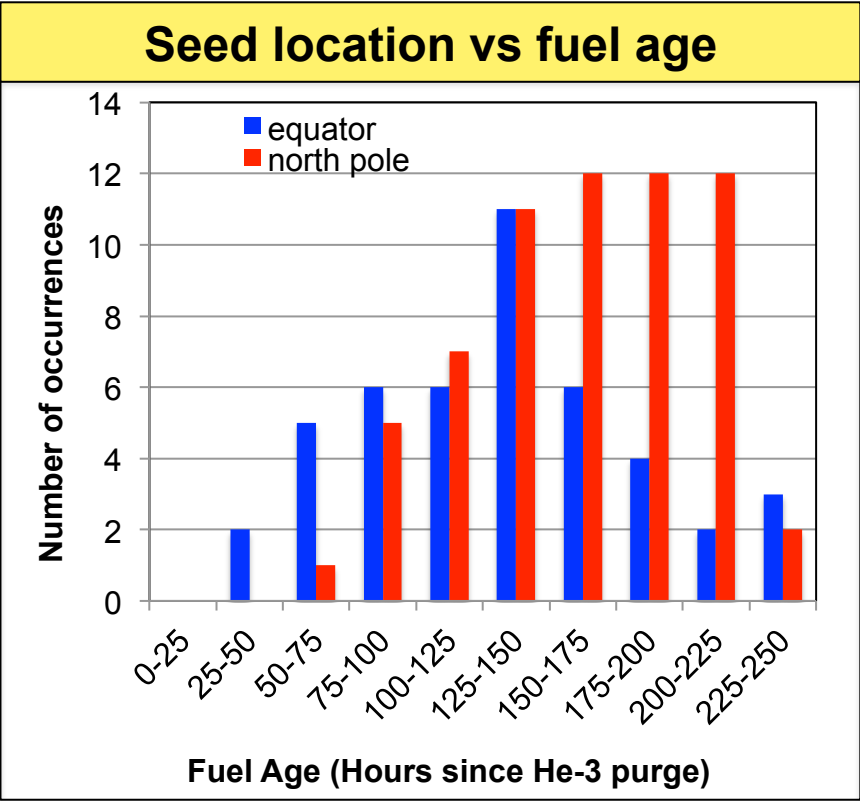
Current seeding process has several failure modes
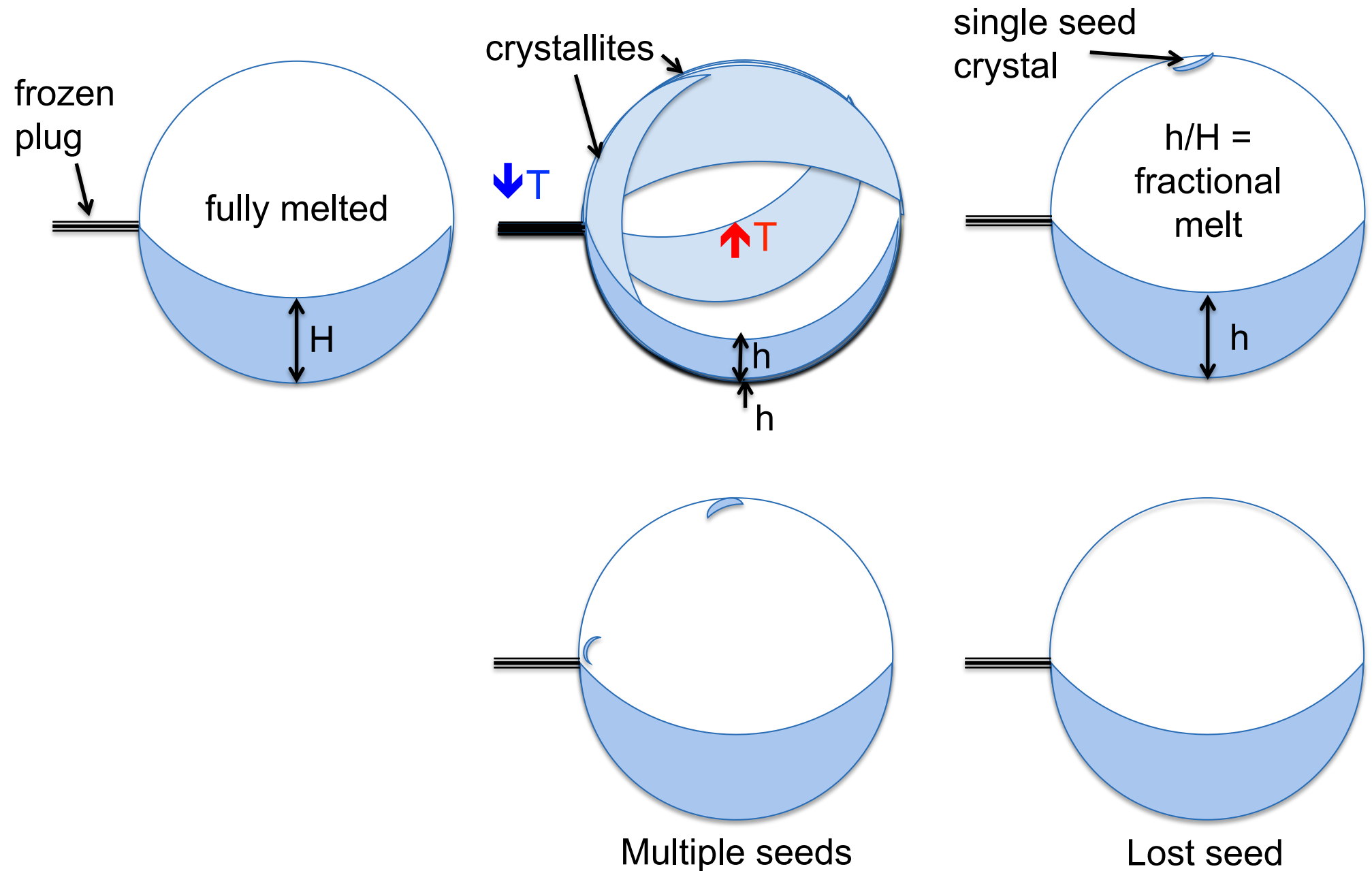
Seed migration is observed to be faster in layers formed in B581 than in proofing station

- Data suggests that proofing station fill process delivers less ^{3}He (or H_2) to capsule than B581
- We are working to identify the difference

Seed location vs fuel age

Number of occurrences

- equator
- north pole

14
12
10
8
6
4
2
0

Fuel Age (Hours since He-3 purge)

0-25, 25-50, 50-75, 75-100, 100-125, 125-150, 150-175, 175-200, 200-225, 225-250

Cumulative north pole seed probability vs fuel age

Cumulative north pole probability

ITPS
B581

1.2
1
0.8
0.6
0.4
0.2
0

~ 72 hours

Fuel Age (hours)

0   100   200   300   400   500   600

2D finite element model narrows focus of investigation

Mode 1 represented in two coordinate systems
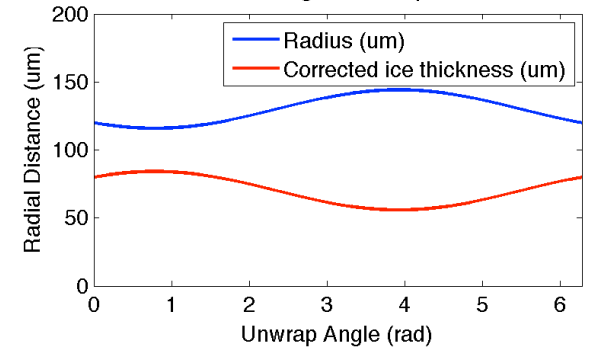
Coordinates used for unwrapping

$A_{cos} < 0$
$A_{sin} < 0$
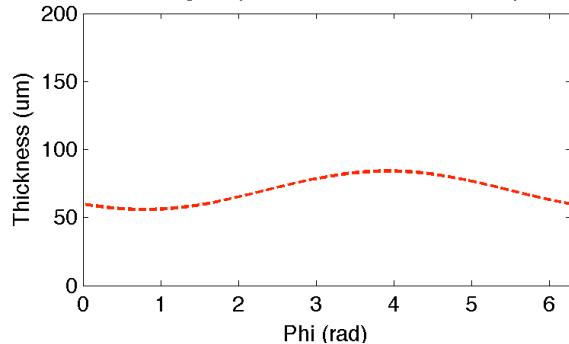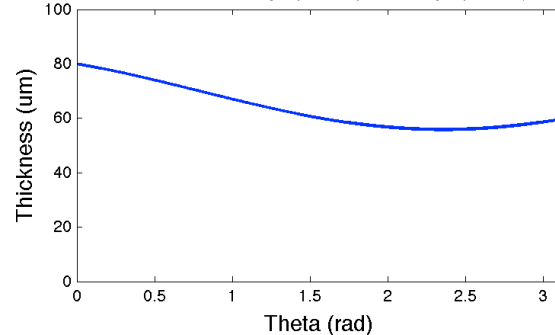

Registered image in unwrap coords
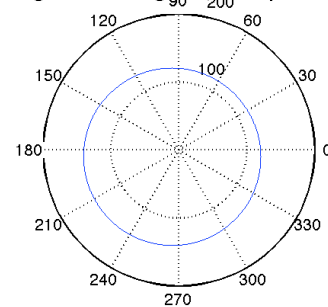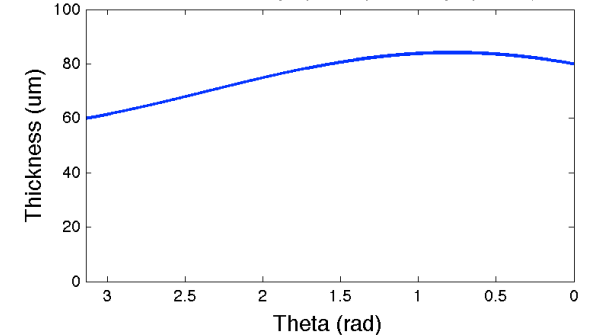

Unrolled image in unwrap coords

LEH ice edge in phi/theta coords: fill tube @ phi = 0

Side View: 5/4*pi (Side2) or 7/4*pi (Side1)

Side View: 1/4*pi (Side2) or 3/4*pi (Side1)

Spherical-polar "Haan-Mapoles" coordinates
(fill tube at phi = 0, theta = 0 at north pole)